Spillway examination guide

FCERM Research & Development Programme

Research report

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Email: fcerm.evidence@environment-agency.gov.uk.

Author(s):
Andrew (Eddie) Robinson

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Research contractor:
Environment Agency
Horizon House, Deanery Rd,
Bristol BS1 5AH

Environment Agency's Project Manager:
Dr Chrissy Mitchell

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Contents

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- The Reservoir Safety Research Advisory Group (ReSRAG) was consulted at 2 important stages to help produce the best possible guide and reduce unintentional oversights. Its views were sought on the:
    1. direction and content of the guidance
    2. draft final guide

Executive summary

This document aims to help identify safety issues sooner at reservoir spillways. It provides guidance on:

1. understanding critical vulnerabilities (study of design, construction and spillway potential failure mechanisms)
2. examining and inspecting via close, physical access or equivalent methods
3. observing the spillway in a range of operating conditions
4. investigating visual warning signs
5. monitoring change and routine surveillance

The guidance concentrates on examining concrete spillways, presents case studies and consolidates global good practices and lessons from incidents. A significant amount of the content is transferable to other types of reservoir spillways. For example, a review of technical information and spillway potential failure mechanisms will help identify the critical elements of the spillway system that require inspection.

The content is relevant to reservoir managers and undertakers, as well as supervising engineers and inspecting engineers concerning 'high risk' reservoirs in England and Wales. Representatives from each audience were involved throughout the guidance development.

The content could also apply to:

- 'high-risk' reservoirs and 'medium-risk' reservoirs in Scotland
- 'high consequence' reservoirs and 'medium consequence' reservoirs in Northern Ireland when the relevant section of the Reservoirs Act (NI) 2015 commences

Reservoir managers and undertakers of other reservoirs may benefit from transferable information on:

- arranging safe entry by direct access and equivalent methods (Chapter 5)
- visual warning signs of potential vulnerabilities (Chapter 6)
- insights by practitioners on creating an investigation strategy and choosing techniques to detect issues (Chapter 7)
- techniques to identify and track changes in cracks, movement and seepage

The guidance contains information on a range of techniques that were known when the research was completed in 2021, including emerging techniques. Before commissioning work, it is recommended to perform a search to identify any updates or new ones that have become available.

1. Introduction

1.1. Guidance background

On 1 August 2019 there was a failure of the auxiliary spillway (built in 1970) at Toddbrook Reservoir. This led to the precautionary evacuation of 1,500 people from the downstream town of Whaley Bridge. Two reports were published in February 2020 that investigated the incident:

- ‘Toddbrook Reservoir Independent Review Report’ by Professor David Balmforth, commissioned by the Secretary of State for Environment, Food and Rural Affairs
- ‘Report on the Nature and Root Cause of the Toddbrook Reservoir Auxiliary Spillway Failure on 1st August 2019’ by Dr Andy Hughes, commissioned by the Canal & River Trust in accordance with the Reservoirs Act 1975

This guide addresses the following relevant Balmforth recommendations:

- Recommendation 1 – The Environment Agency commissions new guidance on the failure mechanisms of spillways and how to undertake spillway inspections. This should include guidance on spillway design based on international good practice and lessons learned from incidents in the UK.
- Recommendation 2 – Inspecting engineers and supervising engineers inspect spillways closely and by direct access during their visits, with a minimum of one year between supervising engineers’ spillway inspections.
- Recommendation 3 – The owner should make the necessary safety preparations in advance to enable such close inspections to take place as a matter of routine.

Spillway failure mechanisms have been investigated by a separate guide (Environment Agency, 2022a) to address part of Recommendation 1, which has informed the development of this guide. Spillway design is covered in a separate guidance due to the different users and needs. Both are referenced in this guide where appropriate.

1.2. Guidance objective

This document aims to change behaviours so that:

1. close and safe inspection of spillways by direct access becomes the norm for inspecting engineers
2. a supervising engineer closely examines critical elements of a spillway by direct access or using an equivalent method at least once every 12 months
3. major deficiencies are identified earlier
4. public safety is maintained

1.3. Intended users

The content applies to reservoir managers and undertakers[1], as well as supervising engineers and inspecting engineers in relation to 'high risk' reservoirs in England and Wales.

The content could also apply to:

- 'high-risk' reservoirs and 'medium-risk' reservoirs in Scotland
- 'high consequence' reservoirs and 'medium consequence' reservoirs in Northern Ireland

The technical information in chapters 5 to 8 may also be useful to other reservoir managers and undertakers if their reservoirs have a spillway.

1.4. Guidance scope

The focus of this guidance is on consolidating global good practices and lessons from incidents that will help the inspection and examination of concrete, ungated spillways[2] similar to Toddbrook Reservoir. The principles contained in the guide are also transferable to other spillways, for example masonry and reinforced grass. For the examination of reservoir conduits and shaft[3] spillways, refer to 'Dam and reservoir conduits. Inspection, monitoring, maintenance and repair' (CIRIA, 2015).

The guide will support periodic inspections[4] by inspecting engineers, visits by supervising engineers and routine surveillance by reservoir managers/undertakers.

Further guidance for reservoir managers/undertakers on spillway monitoring can be found on GOV.UK.

1.5. Guidance structure

The guide is ordered as follows:

- Chapter 2 – Important principles

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[1] Collectively called 'Owners' by Professor David Balmforth.

[2] A spillway typically consists of 4 components: an inlet structure, a control structure, a conveyance structure/channel and an energy dissipation structure.

[3] Also known as a bellmouth and a 'Morning Glory'.

[4] Defined by national reservoir legislation and known as Section 10 inspection in England and Wales, Section 47 inspection in Scotland, and maybe referred to as a Section 35 inspection in Northern Ireland when the relevant section of the Reservoirs Act (NI) 2015 is commenced.

- Chapter 3 – Preparation for a periodic spillway inspection
- Chapter 4 – Preparation for a spillway visit by a supervising engineer
- Chapter 5 – Arranging safe access
- Chapter 6 – Examination and visual warning signs
- Chapter 7 – Techniques for investigating vulnerabilities
- Chapter 8 – Techniques for monitoring

At the end of some of the chapters, there is a list of useful publications that provide further technical details. The lists are not intended to be exhaustive, but rather encourage further reading and learning. Chapter 10 provides a list of references that informed the guidance. Appendices contain further supporting information and case studies that help illustrate the content of the chapters.

To increase the usability of the guide, **Table 1.1** indicates the target audience for all chapters, appendices and, as necessary, specific sections.

Table 1.1: Target audience of each chapter and important sections in the guide

Chapters and sections in the guide	Reservoir manager/ undertaker	Inspecting engineer	Supervising engineer
Section 2.2: Reservoir manager/undertaker facilitates spillway examinations and inspections	Target audience	Have an awareness	Have an awareness
Section 2.3: Periodic spillway inspection by an inspecting engineer (supplemented by Appendix A1)	Have an awareness	Target audience	Have an awareness
Section 2.4: Spillway examination by a supervising engineer (supplemented by Appendix A2)	Have an awareness	Have an awareness	Target audience
Section 2.5: Routine spillway surveillance	Target audience	Have an awareness	Have an awareness
Section 3.2: Planning ahead for a periodic spillway inspection	Target audience	Have an awareness	Have an awareness
Section 3.3: Technical evaluation[5] before a spillway inspection (supplemented by Appendix B[6])	Have an awareness	Target audience	Have an awareness
Chapter 4: Preparation for a spillway visit by a supervising engineer (supplemented by Appendix C)	Have an awareness	Have an awareness	Target audience
Section 5.2: Planning and arranging safe physical access (supplemented by Appendix D)	Target audience	Have an awareness	Have an awareness
Section 5.3: Planning and arranging equivalent means of access, inspection or observation	Everyone	Everyone	Everyone
Chapter 6: Examination and visual warning signs (supplemented by Appendix E)	Everyone	Everyone	Everyone
Chapter 7: Techniques for investigating vulnerabilities (supplemented by Appendix F)	Target audience	Have an awareness	Have an awareness
Chapter 8: Techniques for monitoring	Target audience	Have an awareness	Target audience

[5] This includes spillway potential failure mechanisms

[6] This contains factors affecting vulnerability

2. Important principles

2.1. Overview

This chapter presents the interpretation of particular recommendations from the Toddbrook Reservoir Independent Review Report.

2. "Inspecting Engineers and Supervising Engineers inspect spillways closely and by direct access during their visits, with a minimum of one year between Supervising Engineers' spillway inspections."
3. "The Owner should make the necessary safety preparations in advance to enable such close inspections to take place as a matter of routine."

Each role mentioned in these recommendations has a sub-section. These explain how the recommendations should be implemented in practice and indicate when exceptions should apply.

A sub-section on routine maintenance by the reservoir manager/undertaker is included at the end of this chapter, section 2.5. While this is not explicitly referred to in the recommendations, it is integral to reservoir safety management.

All sub-sections contain cross-references to useful parts of this guide.

2.2. Reservoir manager/ undertaker facilitates spillway examinations and inspections

Recommendation 3 is succinct: "The Owner should make the necessary safety preparations in advance to enable such close inspections to take place as a matter of routine." It has 3 clear and crucial components:

a. Responsibility to facilitate the inspection of spillways lays with the reservoir manager/undertaker – this follows reservoir safety legislation[7].
b. Safety arrangements should be planned in advance – this is good practice.
c. Close, physical access should be customary – this makes any examination possible.

[7] See Section 21 (5) in the Reservoirs Act 1975, Section 97 in the Reservoirs (Scotland) Act 2011, and may be referred to as a Section 98 in Northern Ireland when the relevant section of the Reservoirs Act (NI) 2015 is commenced.

To satisfy these components, the reservoir manager/undertaker should lead the creation of an access strategy (section 5.2). This will improve their health and safety risk assessments for any spillway examination and inspections.

When making advance arrangements for the periodic spillway inspection, the reservoir manager/undertaker should consult with the inspecting engineer. Planning ahead is fundamental to ensure that:

- spillway drawings and information are provided to the inspecting engineer far enough in advance to evaluate potential failure modes and plan their inspection
- the inspecting engineer can satisfy section 2.3 principles
- arrangements facilitate the default approach, a close-up examination when the spillway is not operating. This can include lowering the reservoir top water level and cleaning surfaces so that the joints can be seen properly

Section 3.2 provides a recommended schedule of tasks that may allow a successful inspection.

If the spillway is or is likely to be operating the day before the inspection, despite reasonable efforts to provide safe and direct access, the reservoir manager/undertaker should inform the inspecting engineer, who will decide whether the inspection should proceed.

Regarding the supervising engineer visits, the reservoir manager/undertaker should consult with them to ensure the directions by the inspecting engineer and any additional monitoring can be fulfilled. If the last inspection report does not contain spillway directions, the reservoir manager/undertaker should refer to the Environment Agency’s Technical Bulletin regarding Toddbrook (dated 19 March 2020).

2.3. Periodic spillway inspection by an inspecting engineer

Appendix A1 contains the context for the principles in this section.

Before the visit, an inspecting engineer should review technical information and consider spillway potential failure mechanisms. This will identify the critical elements of the spillway system that need to be inspected. **Chapter 3** provides supplementary guidance and refers to useful technical publications. If there are knowledge gaps following the technical evaluation, the inspecting engineer can still proceed with the inspection.

An inspecting engineer should, wherever practicable and safe to do so, inspect the critical elements of a spillway closely using direct access methods (be within touching distance). So that the surfaces of the spillway can be properly inspected, the reservoir manager/undertaker should create a safe method of access. This might include drawing down the reservoir water level and cleaning the surfaces. For example, algae or moss should be removed so that the joints can be seen.

An inspecting engineer may choose an equivalent method of inspection if they:

- cannot safely access within touching distance part or parts of the spillway
- determine there is a low potential for a defect at such locations to develop into a safety issue

Examples of equivalent methods of inspection are presented in **section 5.3**. For example, a drone[8] can provide close, real-time, high definition video.

If the spillway is operating the day before the inspection, perhaps despite significant efforts by the reservoir manager/undertaker, an inspecting engineer could:

- arrange another visit for a physical spillway inspection
- choose an equivalent method of inspection that can be safely implemented
- request recorded footage of the spillway when it is not operating

Whenever an inspecting engineer chooses an equivalent method of inspection, they should record the justification in the inspection report and acknowledge the limitations of the approach.

An inspecting engineer should, if possible, observe the spillway in a range of operating conditions. This can be based on recorded footage and photographs supplied by the reservoir manager/undertaker.

An inspecting engineer should list and comment on the significance of any visual warning signs through the study of available design and construction information and, when needed, field investigations. **Chapter 6** Chapter 6 presents examples of visual warning signs.

The inspecting engineer should also record details on the condition of the spillway in the inspection report. This will assist future visits by supervising engineers and the next statutory inspection. To address any knowledge gaps, the inspecting engineer should consider recommending measures in the interests of safety. If there is an interim cause for concern, the inspecting engineer should recommend precautionary measures to mitigate any actual or perceived risks. Further guidance on this can be found on GOV.UK.

When the inspecting engineer produces the inspection report, they should state:

- future methods of access/observation
- expected frequency of visits by a supervising engineer
- the spillway potential failure mechanisms
- critical elements of a spillway
- aspects to monitor and frequency of surveillance

[8] Sometimes referred to as a UAV (Unoccupied aerial vehicle).

2.4. Spillway examination by a supervising engineer

Appendix A2 contains the context for the principles in this section.

A supervising engineer should closely examine critical elements of a spillway by direct, physical access or using an equivalent method of examination/ observation at least once every 12 months.

The reservoir manager/ undertaker is responsible for enabling safe, physically close examination as a matter of routine. If the supervising engineer feels at any time that hazards have not been mitigated safely or they are not comfortable with the access system, they should record the reason in their annual statement and select an equivalent method of examination/ observation. There are 3 broad types of equivalent methods of examination/ observation; examples of them, as well as insights are presented in section 5.3:

- Remotely from a safe vantage point
- Using a specialist with video equipment
- Using a remotely operated vehicle and/ or unoccupied aerial vehicle

If the spillway is normally operating, the supervising engineer should consult with an inspecting engineer – ideally the one who completed the last inspection – to agree when to closely examine it off-spill and if it should be in person or via a video recording. The inspecting engineer may recommend continuing with an equivalent method of examination/ observation (when the spillway operates) if they can demonstrate there is a low potential for a defect to develop into a safety issue. Evidence may relate to design, age, condition, category and consequence. If the evidence is not convincing, the supervising engineer should examine the spillway when it is not operating. The supervising engineer should record any change in direction in Part 10 of the Prescribed Form of Record.

In preparation for a close examination, the supervising engineer should review the most recent inspection report. When there is no specific mention in the last inspection report about expected frequency or type of monitoring, the supervising engineer should refer to the Environment Agency's Technical Bulletin regarding Toddbrook (dated 19 March 2020). They could also have a conversation about the following matters with an inspecting engineer, ideally the one who completed the last inspection:

- methods of access/observation
- frequency of visits
- observing different spillway conditions
- spillway failure mechanisms
- critical elements of a spillway
- historical investigations at/near the spillway
- potential signs of vulnerabilities
- any relevant measures in the interests of safety

- aspects to monitor

Chapter 4 offers other activities to help a supervising engineer be as prepared and informed as possible before a spillway visit.

If the supervising engineer spots new visual warning signs (as presented in Chapter 6), they should consider if there is an urgent safety concern to the reservoir and follow the onsite emergency plan. An understanding of the spillway potential failure mechanisms and critical spillway elements will assist the decision-making.

Where there are new warning signs and there is not an imminent threat, the supervising engineer must instruct the reservoir manager/undertaker on the need for additional examination. This allows evidence to be gathered before the next periodic inspection or prior to calling for one. Additional examination could be capturing visual footage of the entire spillway in different conditions, for example, whenever it operates, just after dewatering and when off-spill. Chapter 4 contains useful guidance and will help preparation for the spillway examination.

If a supervising engineer is in any doubt at any time, they should first have a conversation with an inspecting engineer, ideally the one who completed the last inspection. Situations that merit this approach include considering repairs to treat any visual warning signs that appear minor (Chapter 6).

2.5. Routine spillway surveillance

Routine surveillance by the reservoir manager/undertaker plays an integral part in dam safety. While this activity is not covered by a recommendation, there are important considerations as a result of the Toddbrook Reservoir Independent Review Report. It is acknowledged globally that frequent visual observation by trained and untrained eyes can spot signs of change early.

It is crucial that the reservoir manager/undertaker arranges routine spillway inspections. These are typically once a week, but can be daily if a specific risk justifies it. The reservoir manager/undertaker should look at the past inspection report and consult with the supervising engineer on the frequency and scope of the inspections. Chapter 6 contains useful information on visual warning signs.

The reservoir manager/undertaker must notify the supervising engineer of each visual inspection when anything untoward is noticed. Findings should be recorded, ideally digitally as a photograph or video. Appendix C2 provides insights on recording visual footage to improve its usefulness.

The inspecting engineer gives directions regarding information to be recorded and monitored over the period up to the next inspection. If any relate to a spillway, Chapter 8 contains useful information on monitoring techniques to track change.

2. Preparation for a periodic spillway inspection

3.1. Overview

This chapter focuses on activities before a spillway examination on site as part of a statutory periodic inspection. It is divided into 2 parts:

- **Section 3.2** – building on the principles in Chapter 2, various steps are proposed to help arrange the physical inspection. It aims to instil planning ahead so that the spillway can be adequately examined. The primary audience is the reservoir manager/ undertaker
- **Section 3.3** – focuses on technical evaluations by the inspecting engineer before visiting the spillway. This includes analysing potential failure modes that will help detect potential defects and guide the inspection effort. Some of the considerations can help, to a degree, mitigate situations when there is limited information or no design/construction drawings. The primary audience is the inspecting engineer.

3.2. Planning ahead for a periodic spillway inspection

The reservoir manager/undertaker should devise a schedule of tasks in agreement with the inspecting engineer and supervising engineer. A staged approach is recommended, such as:

- Step 1 – Reservoir manager/undertaker, assisted by the supervising engineer, reviews guidance on preparing an inspection information pack[9] and collates the best relevant information[10]. A review of certificates and the previous inspection report may help detect gaps. The Institution of Civil Engineers' archives may have historical records of the design and construction of the spillway or similar spillways elsewhere.
- Step 2 – Reservoir manager/undertaker commissions the inspection with enough time before the previous inspection period expires. Given the following steps and arranging safe access, it is anticipated that commissioning process begins at least 12 months ahead of inspection. The time for arranging future inspections could be shorter.

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[9] https://www.gov.uk/guidance/reservoir-owner-and-operator-guidance-inspection-information-pack.

[10] This should include the design report and associated detailed drawings, flood study with design spillway outflow, historical repairs and monitoring (charts, photographs, videos).

- Step 3 – Reservoir manager/undertaker creates a risk assessment and access strategy (Chapter 5).
- Step 4 – Arrange date for inspection, allowing for any necessary draw down.
- Step 5 – Reservoir manager/undertaker provides specific information to help the inspection, assessment of spillway condition and its adequacy.
- Step 6 – Technical evaluation by the inspecting engineer (section 3.3).
- Step 7 – On the date of the physical inspection, reservoir manager/undertaker checks the safety of the access system and completes a dynamic risk assessment using their own procedures.

If any of the tasks cannot be completed to the inspecting engineer's satisfaction, there are 2 possible outcomes:

a) The date of the inspection is re-arranged until tasks are completed satisfactorily.
b) The inspecting engineer cannot make a determination on the spillway and recommends measures in the interests of safety along with precautionary measures as necessary.

3.3. Technical evaluation by the inspecting engineer before a spillway inspection

3.3.1 Drawing on lessons from incidents

This section draws on lessons from spillway incidents across the world and useful literature on inspecting spillways (section 3.4). It is divided into:

- evaluating information
- suggesting spillway potential failure mechanisms

These will help the inspecting engineer when they assess the spillway condition and performance. In order to minimise the risk of becoming 'blinkered', it is recommended that the inspecting engineer continues to stay curious when considering the insights.

3.3.2 Evaluating information

The inspecting engineer should perform a comprehensive review of the Reservoir Inspection Package of Information. Typically, each inspecting engineer develops their own method to evaluate the information. Some universal principles are presented here to help spot design weaknesses and potential vulnerabilities. **Appendix B1** contains supplementary information.

- Think like a detective – the overarching principle to apply throughout and can help deduce as-built features when drawings are not available.
- Identify the spillway design/assumptions – collating facts.

- Consider if there are any features that are not typical to other spillways – comparisons.
- Look at how the spillway was constructed – construction problems or design deviation.
- Consider the evolution/life of the spillway condition – changes since construction.
- Understand the performance maintenance – frequency of clearing the spillway and its drainage.

3.3.3 Postulating spillway potential failure mechanisms

When the inspecting engineer considers how failure of the spillway system could impact the integrity of the dam, it is important to acknowledge that the failure definition should be broader than an uncontrolled release of water. This widens the postulated spillway failure mechanisms and increases the chance that critical spillway defects are identified and given attention earlier. The research paper by the Environment Agency (2022a) suggests using the following definition for a spillway failure:

“a condition where the spillway can no longer reliably perform its intended function to ‘pass normal (operational) and/or flood flows in a manner that protects the structural integrity of the dam”

The research paper studied a total of 59 documented spillway failure incidents and systematically redefined failure mechanisms into 2 broad categories: stability failure and structural failure. Sub-categories are also presented based on root-cause analysis, noting that there are often several factors associated with them. Table 3.1 presents the failure mechanisms in relation to concrete spillways. Potential causes (initiation and progression) are fully explained in the Environment Agency publication (2022a). The effects of internal and external erosion are considered as contributing factors to the spillway failure mechanisms.

Table 3.1: Potential failure mechanisms in relation to concrete spillways

Failure mechanism	Sub-category	Description
Stability	Due to uplift	Occurs where the external hydrostatic pressure acting on the spillway structure (from groundwater or surface water, including tailwater) exceeds its own self-weight, added weight of water, any added weight of soil and friction and the weight of any rock or soil mass mobilised by anchors.
Stability	Due to overturning	Occurs where there is an increase in loading on masonry walls that could result in internal tensile stresses, causing overturning of the walls.
Stability	Due to sliding	Occurs where the shear strength at the spillway foundation is insufficient to resists. the sliding forces acting on the structure. This failure mechanism is characterised by a relatively high degree of uncertainty relating to the estimation of the geotechnical parameters governing the resistance to sliding. Could also occur as a result of an increase of the sliding forces acting on the structure.
Structural	Due to excessive uplift pressure	Occurs where the uplift pressure acting on the spillway base slab/armour layer exceeds the design pressure. While uplift stability failure may not occur (due to the effects of friction or other favourable effects and/or safety factors), ultimate limit strength and/or serviceability limit strength structural failures could occur as a result of the increased bending moments.
Structural	Due to loss of side support and undermining	Occurs where the spillway walls lose their side support, or the spillway foundation is weakened as a result of external or internal erosion, for example, external erosion due to spillway overtopping, internal erosion due to seepage, or external erosion downstream of energy dissipators. Such erosion and undermining could cause the structure to collapse under the action of its own weight and any added internal hydrostatic or other action.
Structural	Due to excessive or unaccounted dynamic actions	Occurs where some of the dynamic actions inherent to the spillway operation have not been adequately accounted for. Such dynamic actions may include mean hydrodynamic forces, flow-induced vibrations, vibrations due to wind turbulence, wave action and dynamic impact from floating debris and/or ice.
Structural	Due to cracking and corrosion of reinforcement	Occurs where cover is insufficient, cracking is excessive, and reinforcement is exposed to corrosion. This would progressively reduce the strength, and therefore the durability, of the reinforced concrete structure. Can occur through design/construction deficiencies and several failure mechanisms, for example, excessive uplift pressures, loss of side support and undermining, excessive or unaccounted dynamic actions.

Once the inspecting engineer has suggested the potential failure mechanisms, they should make a list of physical factors that contribute to them. Appendix B2 and Appendix B3 contain lists of factors that affect vulnerability. Establishing a good understanding of spillway vulnerabilities and associated potential failure mechanisms helps identify critical defects during the physical inspection. It is good practice to make a sketch of an event/sequence tree to appreciate if a feature contributes to a spillway failure.

3.4. Further reading

The following publications will provide more context when performing a technical evaluation:

- SCHWEIGER, S., KLINE, R., BURCH S., WALKER, S.R. 2019. You Don't Know What You Don't Know. Inspecting and assessing spillways for potential failure modes. In Sustainable and Safe Dams Around the World – Tournier, Bennett & Bibeau (Eds), Canadian Dam Association, ISBN 978-0-367-33422-2. pp2027-2038.

- USBR, 2019. The Dam Safety Risk Analysis Best Practices Training Manual.
- FIROOZFAR, A.R., DOSANJH, K., MOEN, K.C., ZAPEL, E.T., AND FORD, T. 2018. Generalized Programmatic Framework for Spillway Inspection and Potential Failure Modes Assessment, Proceedings of U.S. Society on Dams Conference, Miami, Florida, April 30 - May 4, 2018.
- CALIFORNIA DEPARTMENT OF WATER RESOURCES, 2018. Independent Forensic Team Report, Oroville Dam Spillway Incident. January 2018 (Final May 2018). Appendix E – Review of Spillway Chute Design Practices.
- MASON, P.J. 2017. Spillway chutes: Practical design considerations and details. Hydropower & Dams Issue Five, 2017 – design details.
- TROJANOWSKI, J. 2006. Can your spillway survive the next flood? The role of dams in the 21st century: 26th Annual USSD Conference, San Antonio, Texas. May 1-5, 2006.

3. Preparation for a spillway visit by a supervising engineer

4.1. Overview

This chapter focuses on steps to help a supervising engineer be as prepared and informed as possible before a spillway visit. It builds upon the principles in section 2.4. It also draws on lessons from spillway incidents across the world and relevant literature. The chapter is divided into 3 steps that will help decision-making, the detection of potential defects and guide the examination effort:

- Step 1 – Understanding the spillway (section 4.2)
- Step 2 – Consulting with an inspecting engineer (section 4.3)
- Step 3 – Consulting with the reservoir manager/undertaker (section 4.4)

4.2. Understanding the spillway

A supervising engineer should have an awareness and understanding of:

- the spillway's components – typically from drawings
- the spillway's 'as-built' detailing and composition – typically from drawings
- the inspecting engineer's assessment of the spillway potential failure mechanisms – helps appreciate inherent vulnerabilities and components where changes in condition is critical
- the previous supervising engineer's annual statements – if there has been a recent change in personnel
- the general condition of the spillway from the previous inspection report – helps identify significant changes
- the past condition of specific aspects/matters to be watched as set by the inspecting engineer – helps understand scope of the visit and spot trends and/or changes
- past investigations and repairs at the spillway – specific places to watch
- ongoing monitoring – to detect trends and/or changes

More information on these matters is covered in section 3.3. The reservoir manager/undertaker should provide this information to the supervising engineer.

4.3. Consulting with an Inspecting Engineer

For a supervising engineer's first visit to the spillway, they should refer to the previous inspection report. If they have concerns about the safety of the reservoir, they should have a conversation with an inspecting engineer, ideally the one who completed the last inspection, about the following matters:

- limited/ lack of information
- frequency of visits and critical elements to watch
- methods of access/observation
- how often to closely examine the spillway off-spill
- visual footage of the spillway in different operating conditions

Appendix C1 provide quotes from publications that will help conversations and decision-making on the frequency of visits and methods of access/observation. They emphasise that the past is not always a good indication of the future, timing is everything, and the benefits of physical examination are globally acknowledged.

4.4. Consulting with the reservoir manager/ undertaker

The supervising engineer should liaise with the reservoir manager/undertaker to confirm requirements that help their visit. This could include, but is not limited to:

- arrangements for close, safe access to critical components of the spillway
- capturing visual footage of the spillway in different operating conditions and times of the year (**Appendix C2** gives good and bad practices)
- progress on any actions or maintenance since the previous visit

4. Arranging safe access

5.1. Overview

This chapter covers how to plan for and enable safe physical access for an inspecting engineer or a supervising engineer. The chapter is separated into:

- strategy for creating safe, physical access (section 5.2)
- considerations for using equivalent methods of access, inspection or observation (section 5.3)

The reservoir manager/undertaker is responsible for facilitating the access. They should work with the supervising engineer and the inspecting engineer to create suitable and timely safe access to the spillway. Supplementary guidance and information are contained in Appendix D.

Some considerations in this chapter may also help the reservoir manager/undertaker when arranging detailed investigations into vulnerabilities.

5.2. Planning and arranging safe physical access

5.2.1 Health and safety

The primary objective is to enable safe, physical access to a spillway in order to assess its condition. While an inspection ultimately focuses on safeguarding people downstream of a dam, the safety of the personnel performing the examination is crucial. It is the responsibility of the reservoir manager/undertaker to provide a safe working environment. It is imperative that examination of a spillway is managed to comply with general statutory and other relevant health and safety requirements. This includes any associated regulations and approved codes of practice and guidance documents that amplify the requirements.

In line with the Management of Health and Safety at Work Regulations 1999, the reservoir manager/undertaker should develop and maintain a health and safety risk assessment for any spillway examination. Advice from appropriately trained health and safety professionals should be sought. They should be familiar with the Work at Height Regulations 2005. The Health and Safety Executive website provides useful and up-to-date guidance on the regulations.

Appendix D1 provides some further information on the Work at Height Regulations, such as a hierarchy of measures for preventing any person falling a distance likely to cause personal injury. The requirement is to choose the least hazardous method and equipment that is reasonably practicable to perform the task adequately. For a close inspection, it might not be possible to avoid working at height and so hazards should be mitigated accordingly to prevent falls.

To help select the most appropriate methods and necessary equipment, it is beneficial to produce an access strategy. The reservoir manager/undertaker should liaise with the supervising engineer and inspecting engineer when creating the access strategy. The following section provides a list of considerations to help develop an access strategy.

5.2.2 Developing an access strategy

There are many different kinds of reservoir spillways, each with their own individual characteristics, Figure 5.1 illustrates a range of these. A well-developed access strategy will help to allow safe physical access to any part of a spillway. When developing an access strategy, a detailed risk assessment should be carried out, ensuring that the design, installation, use, maintenance and ultimately decommissioning of each option is considered. This sub-section focuses on spillway-oriented questions that will support the development of an access strategy.

Figure 5.1: A variety of spillways. A). Steep chute at Llyn Brianne Dam, Wales (Source: Jonathan Hinks). B) Buttress dam spillway at Clywedog Dam, Wales (Source: Severn Trent). C) Operating spillway at Pitsford Reservoir, England (Source: Andrew DC Robinson). D) Concrete spillway at Fruid Dam, Scotland (Source: Scottish Water)

Consideration 1: What is the scale of the dam and type of spillway?

The scale of the dam and type of spillway can influence the need for more than one method of access. Taking a strategic and holistic approach can help the inspection and management of hazards. The following are examples of strategic approaches:

a) View the whole spillway using a remotely operated vehicle, then carry out targeted, close and physical examination.
b) Only carry out close and physical examination.
c) Carry out close and physical examination, supplemented with other methods of inspection/observation.

Consideration 2: What features should be inspected?

It can be useful to create a detailed examination plan to identify all the features to be inspected and then consider how to gain access to each of them safely. Known problems or defects, or areas of potential problems can influence the approach and access requirements. Preparing an examination checklist may help to identify specific examination objectives, which can be useful in developing the risk assessment and the inspection report.

Where regular examination is to be carried out, the examination plan and checklist can be developed into a safe system of work to be followed on each occasion. If a checklist is created, a reservoir manager/undertaker should consider ways to mitigate the risk of complacency, such as identifying triggers to review it with the supervising engineer and/or inspecting engineer.

Consideration 3: When is the best time for physical access?

It is better to physically examine a spillway when it is not operating. This may remove some of the safety hazards or dependence on specialists. For example, the upstream face of the inlet structure may not require underwater examination. The time of the year or season can influence the opportunity to see features that are usually submerged. Conversely, environmental protection measures can limit the times during which a large amount of water may be released from the reservoir.

The reservoir manager/undertaker should liaise with the inspecting engineer and supervising engineer to make arrangements for the reservoir water level to be drawn down and, if necessary, components of the spillway to be dewatered and cleaned. Wave action should be taken into account when deciding on a suitable water level.

With sufficient planning, the examination can overlap with scheduled maintenance or periods of limited operational requirement. An inspection or examination in the winter or spring can be an ideal time as a lower water level gives more flood storage and typically there are weather conditions afterwards to quickly replenish water levels.

Consideration 4: What access systems exist to enter each spillway component safely?

This consideration may reveal 2 matters that require time to address:

1. Special training sessions are needed to use an access system.
2. Some spillway components are inaccessible and require retrofitted solutions or equivalent methods of access (observation).

It is recommended that the reservoir manager/undertaker involves a work at height specialist/consultancy/contractor as they bring insights that help create better and safer solutions. In developing access systems for entry to spillway components, the following aspects should be well understood and are covered in more detail in Appendix D2:

- obstruction to flow/impact on spillway hydrodynamics
- required training, certifications and/or qualifications
- required maintenance
- installation risks
- security and vandalism risks
- protection of the public
- cost to install and annual maintenance costs
- time to install

5.3. Planning and arranging equivalent means of access, inspection or observation

5.3.1 Risk assessment and safe methods

If the inspecting engineer or supervising engineer decide they cannot safely touch part of the spillway when it is not operating, other methods of examination can inform the condition assessment. This does not mean that the other methods of access have no risks associated with them. The risk assessment should be updated for the equivalent methods of access, inspection or observation and any shortfalls duly mitigated. It is recommended that the reservoir manager/undertaker involves a work at height and, if necessary, a confined spaces specialist as they bring insights that help create better and safer solutions.

5.3.2 Equivalent methods of access, inspection or observation

When evaluating an equivalent method, it should be compared against the benefits of an examination or inspection from touching distance. If an equivalent method is chosen, record the justifications in the appropriate document (the inspection report or annual statement).

There are 3 broad types of equivalent methods:

1. Remotely by the inspecting or supervising engineer – looking at the spillway components from a safe vantage point. This can be improved by using a pair of binoculars, a camera on a long reach pole or a camera/video camera with a telephoto lens.
2. Remotely via a specialist – real-time viewing or recorded via video equipment that is attached to a specialist who is within touching distance of the spillway structure. This covers divers, rope access and confined space specialists. The specialist is not expected to make an assessment.
3. Remotely operated vehicle (ROV) and/or unoccupied aerial vehicle (UAV) – highly manoeuvrable machines with mounted video equipment. These can be controlled by radio or through a cable connecting the vehicle to the operator’s location. An ROV is typically used underwater and could help examination in the stilling basin and upstream of the spillway weir. A UAV is sometimes known as a ‘drone’.

The use of some equivalent systems can enhance the quality of an inspection and the recorded data can then be used to identify defects or assist ongoing monitoring and surveillance. However, the equivalent methods can have performance constraints and shortfalls which are often not apparent during consultations with commercial providers. Table 5.1 provides benefits and insights on the equivalent methods to assist decision-making and planning. The insights are not exhaustive nor are they intended to cover every situation.

Two case studies are shown in Appendix D; a rope access to assist a visual inspection of Ryburn Reservoir dam and spillway (Appendix D3); and use of a drone to survey a spillway (Appendix D4).

Table 5.1: A selection of equivalent methods of access, inspection or observation

Access system	Benefits	Insights

Remotely by the inspecting or supervising engineer	• Relatively straightforward to arrange
	  • Relatively few hazards to mitigate
		• Can be time-consuming to record media location. Special cameras automatically record the geolocation.
		• When using a camera or binoculars, balance can be difficult while engrossed in inspecting or observing a structure. Consider a better vantage point or gimbal device for better peripheral vision.
		• Review the quality of media from a safe location.
		  • If using an action camera on a pole, use Bluetooth to show footage on another screen, essentially like CCTV.

Remotely via a specialist in real-time		

	• **Enables hands-on, tactile examination of features in poor visibility**
	• **Panel engineer can direct the specialist to examine specific areas**
	• **Minimal set-up and mobilisation**
	• **Recognised safe system of work**
	  • **Opportunity for specialist to perform structural integrity testing**
		• **Specialists require a reconnaissance visit before the date of the examination.**
		• **Some video cameras offer extra features: hands-free, PPE compatible, noise-cancellation microphone, integrated speaker/audio with hearing protection, high resolution micro display.**
		• **Consider battery life and having back-ups.**
		  • **For a stable connection, if Wi-Fi is not available, need at least 4G when using a Smartphone as a hotspot.**

Remotely via a specialist in real-time		
Diving specialist	• Enables hands-on, tactile examination of features • Panel engineer can direct the specialist to examine specific areas • Opportunity for specialist to perform structural integrity testing (examples shown in **Chapter 7**)	• The HSE Approved Code of Practice (ACoP) and Guidance L104 (2014) guides diving contractors to abide with the Diving at Work Regulations 1997. • SCUBA (self-contained underwater breathing apparatus) is only acceptable for completely benign conditions, that is, no submerged hazards and a 'clear line of sight' between the surface support team and the diver. See ACoP L104 for more details. • Factors affecting the viability of a dive inspection include depth, altitude, water temperature, access, length, currents and visibility. • In poor visibility, a diver can use a 'freshwater box'. The box is placed over the subject and freshwater is piped in, displacing the silt, allowing torchlight illumination. • Daily cost of an equipped diving team can be similar or almost double the cost of an underwater ROV.
Remotely operated vehicle (ROV) and unoccupied aerial vehicle (UAV)		
Underwater ROV	• **Can be configured with a high-definition (HD) video**	• **Some limitations are:**

	camera with high intensity illumination and a sonar mapping system to collect information
	• **Specially designed ROVs can accommodate and operate non-destructive testing equipment**
	    • **Offer live streaming of data**
		- **suspended silt in water reflects torchlight (like headlights in fog) and the images are poor even with sidescan sonar**
		- **restricted mobility in fast currents**
		- **difficulty staying in position in turbulent flows**
		- **2D view might not clearly show full extent of defects**
		• **Good references include:**
		    • **section 9.5.4.3 (p217-21) in FEMA's Technical manual: conduits through embankment dams (2005)**

UAV	• Safe and fast visual examination • Typically, cheaper than rope access • Panel engineer can view real-time footage online and direct the pilot to examine specific areas • Can be equipped with multiple sensors to help identify defects • Can create 2D and 3D maps with geolocation information, as well as Digital twins to help monitoring • Can access vertical and horizontal parts of a shaft spillway • Highly portable and can perform emergency inspections in hard to reach locations or in areas that are unsafe to place personnel	• Rain will affect the quality of the captured data. • 4k video is equivalent to 8.5 megapixels. Images may provide significantly more detail than video. • Piloting a UAV in a spillway is challenging, for example, unusual air movements, GPS[11]/ communications interference, having a good line of sight. • Prior to each flight, a specific risk assessment and flight plan should be prepared. • The Civil Aviation Authority governs the use of UAVs and legislation changes regularly. • A licence to operate does not indicate that a UAV operator is competent to obtain good quality data and process it. Experience in surveying can be a good indicator. Guidance on commissioning UAV survey is given in Appendix A5.

[11] Global Positioning System

6. Examination and Visual Warning Signs

6.1. Overview

Visual defects of spillways are well documented[12] and yet failures occur, such as Boltby 2005, Ulley 2007, Oroville 2017, Todbrook 2019. It is not surprising that experienced reservoir engineers acknowledge the great difficulty to detect subtle signs that indicate a major problem is developing (Trojanowski, 2006, Mason, 2017). A 2005 FEMA publication even states that problems at spillways may not be visible until damage or failure occurs. To make matters more complicated, “failures are seldom the result of a single root cause” (Patrick Regan[13]) and “Past operational history may or may not be any indication of future performance.” (Trojanowski, 2006).

This could indicate that a chapter on examining defects is futile. Or it indicates “the need for dam engineers to question the rules and customs by which we operate.” (p127, Alan Johnstone, 2000)[14]. A similar notion was presented by Albert Einstein[15].

A review of inspection guides, reveals a tendency to indicate the likely reason for a visual defect and provide maintenance advice to restore spillway capacity/ surface flows. While this could be helpful, it could also unintentionally blinker some engineers to treat the symptoms or misdiagnose the cause (Trojanowski, 2006).

To avoid creating an unconscious bias, this chapter refers to visual warning signs and does not relate them to defects or types of damage. Anything that appears to be minor should be investigated unless there is:

- an immediate safety threat and so temporary repairs are required
- evidence that the feature is not critical to the integrity of the dam

The chapter is divided into 3 parts:

- Tools to support the examination (section 6.2)
- Planning an examination/ inspection route (section 6.3)
- Visual warning signs to investigate (section 6.4)

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[12] Veesaert, 2004; Trojanowski, 2006; Young and others, 2010; USBR, 2014; Mason, 2017; Central Water Commission, 2018; Firoozfar and others, 2018; Mason, 2021; Schweiger and others, 2019; Adamo and others, 2020.

[13] Federal Energy Regulatory Commission https://www.nrc.gov/docs/ML1305/ML13059A397.pdf.

[14] BDS Geoffrey Binnie Lecture, titled ‘Taken for Granted’ by Alan Johnstone, 2000.

[15] “Without changing our patterns of thought, we will not be able to solve the problems we created with our current pattern of thought” – Albert Einstein.

6.2. Tools to support the examination

In addition to the access equipment to enable a safe examination (see Chapter 5), there are a few other tools that can optimise the examination:

- Binoculars – They are useful for examining limited-access areas. Regular examination with a pair of powerful binoculars can initially identify areas where change is occurring.
- Heavy chain – A series of chains fastened to a bar can be dragged across concrete and help identify voids qualitatively under a concrete lining.
- Heavy-duty brush – It can help remove small debris and vegetation to check for cracks and holes.
- Metal rod – It can be used to probe joint gaps.
- Tape measure – For determining the size, geometry and location of observed features.
- Tapping device – It can help determine the qualitative condition of support material behind concrete (or asphalt faced dams) and existence of voids by firmly tapping the surface of the facing material. Concrete fully supported by fill material produces a ‘click’ or ‘bink’ sound, while facing material over a void or hole produces a ‘clonk’ or ‘bonk’ sound. The device can be a small hammer or even a length of reinforcing steel.
- Watering can and dye to colour water – To check the degree of crack permeability and where the water emerges.

Further useful equipment is listed in Appendix E1 extracted and adapted from Firoozfar and others (2018).

6.3. An examination or inspection route

It can be helpful to prepare a route in advance of an inspection or examination. Here are some good practices to ensure that all parts of a spillway are examined for vulnerabilities:

- If safe, walk along the entire length of the spillway in a back and forth or zigzag manner.
- Stop periodically and look around for 360 degrees to observe other features from that vantage point.
- Walk alongside the spillway as many times as is required to observe the entire structure.
- Use GPS on a phone or other device to see your recorded route and identify any missed locations.

6.4. Visual warning signs to investigate

6.4.1 What are visual warning signs?

Visual observation can readily detect indications of poor performance. Visual warning signs are anomalous and unusual behaviours that could indicate the development of a failure. This section gives some important findings and warning signs from forensic spillway assessments. It is anticipated that hindsight will inform better decision-making on aspects to investigate. Chapter 7 contains details on how to develop an investigation strategy and testing techniques to determine the existence and extent of vulnerabilities.

If an inspecting engineer chooses not to investigate visual warning signs, they should record the reasons in the inspection report and inform the supervising engineer and reservoir manager/undertaker.

6.4.2 Special considerations

The inspecting engineer and supervising engineer should give special attention to Table 6.1. It contains questions and matters that typically become apparent on site and are learning points from historic spillway failures[16].

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[16] Schweiger and others (2019).

Table 6.1: Special considerations when examining or inspecting a spillway

Special considerations	Reason for the Question	Potential Failure Mechanisms
Is a defect or vulnerability being normalised?	In other words, accepting certain vulnerabilities and conditions of the spillway as 'normal' because they have become expected and, in the absence of any major change, have become accepted. These conditions are often discovered during visual inspections and should become a concern when there is an absence of information into the origin, cause, and comparison to current practice. (p2034, Schweiger and others, 2019).	Any of them
Is woody vegetation growing along or near the spillway?	Trees and other woody vegetation should not be allowed to grow along or near spillways. Tree roots can clog drain systems, displace walls, lift slabs, and obscure defects. The growth of trees along spillways can occur gradually and their impact on the underdrain system can go unnoticed. Some of the trees growing along the Oroville spillway chute were analysed and found to be 49 years old, roughly the same age as the spillway, indicating that they began to grow soon after construction of the spillway was completed. (p2035, Schweiger and others, 2019).	• Stability due to overturning • Stability due to sliding
How is surface water and groundwater managed locally?	Some spillway designs omit measures to limit infiltration of surface water into the backfill, and when measures (such as paving) are provided, their importance is often overlooked and are thus poorly maintained. Additionally, the spillway underdrain system can also intercept groundwater seepage from the abutment, adding to the volume of water than must be conveyed. It is often unclear whether spillway underdrain systems were sized to accommodate these sources of water. (p2035, Schweiger and others, 2019).	• Structural due to loss of side support and undermining
Is the location of drainage outlets appropriate?	A concern with the underdrain system for some spillways is that the drain outlets that are intended to discharge under seepage can also act as inlets for spillway flows to enter the underdrain system and overwhelm the capacity of the drain pipes, resulting in excessive uplift pressures under the spillway slabs. Stagnation pressures or excessive negative pressures can also develop from high-velocity flows over the drain outlets. The flow into the drain outlets, especially those where the flow momentum changes abruptly at the toe of the spillway control section or at the transition to the stilling basin floor, can be a concern as hydrodynamic pressures and stagnation pressures can develop at these. (p2037, Schweiger and others, 2019).	• Stability due to uplift • Structural due to excessive uplift pressure • Structural due to excessive or unaccounted dynamic actions

6.4.2 Examples of warning signs to investigate

Table 6.2 and Table 6.3 provide examples of visual warning signs that should be investigated. They indicate the potential failure mechanism and, where helpful, give descriptions and illustrations of the warning signs. Recognising that each situation is different and that finding the root cause can be complex, no attempt has been made to rank or group the warning signs. Instead, the warning signs have been listed alphabetically. Ultimately, the engineer should make a note of anything that seems to be out of the ordinary, or that could present a safety, maintenance, or operational problem in the future.

Table 6.2: Visual warning signs when the spillway is not operating

Visual warning signs	Potential failure mechanisms	Illustrations/descriptions of signs
Cracking	• Stability failure due to uplift • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to excessive cracking and corrosion of reinforcement	See **Figure 6.1**
Blocked drains or relief wells	• Stability failure due to sliding • Structural failure due to excessive uplift • Structural failure due to undermining	See **Figure 6.2**
Debris in the spillway or at the inlet structure	• Stability failure due to uplift • Structural failure due to loss of side support and undermining • Structural failure due to excessive unaccounted dynamic actions	Debris (for example logs) that temporarily or permanently blocks or reduces the capacity of the inlet or conveyance structure
Debris or accumulated material in the stilling basin	• Structural failure due to loss of side support and undermining • Structural failure due to excessive unaccounted dynamic actions	Debris (for example logs) or material that temporarily or permanently blocks or reduces the capacity of the stilling basin
Deterioration of downstream channel	• Structural failure due to loss of side support and undermining • Structural failure due to excessive unaccounted dynamic actions	Erosion of material near the energy dissipation structure
Disintegration of concrete	• Structural failure due to excessive uplift pressure • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to excessive cracking and corrosion of reinforcement	See **Figure 6.3** and **Figure 6.4**
Disintegration of joints	• Stability failure due to uplift • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to corrosion of reinforcement	See **Figure 6.5** and **Figure 6.6**
Growth of vegetation in the spillway	• Stability failure due to uplift • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to corrosion of reinforcement	Vegetation obstructing surfaces, intrusion of joints and drains, structural impact on side walls from tree growth. See **Figure 6.7**
Growth of vegetation in the stilling basin	• Stability failure due to sliding • Structural failure due to loss of side support and undermining • Structural failure due to excessive unaccounted dynamic actions	Vegetation encroachment

Increased discharge from drains	• Stability failure due to uplift • Stability failure due to sliding • Structural failure due to excessive uplift pressure • Structural failure due to loss of side support and undermining	See **Figure 6.8**
Joint offsets	• Stability failure due to uplift • Stability failure due to sliding • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to corrosion of reinforcement	See **Figure 6.9**
Leakage/ seepage from the concrete floor	• Stability failure due to uplift • Stability due to overturning • Stability due to sliding • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to corrosion of reinforcement	See **Figure 6.10, Figure 6.11** and **Figure 6.12**
Leakage/ seepage near to the spillway	• Stability failure due to uplift • Stability failure due to sliding • Structural failure due to excessive uplift pressure • Structural failure due to loss of side support and undermining	See **Figure 6.13**
Misalignment at retaining walls	• Stability failure due to sliding • Structural failure due to loss of side support and undermining	Look carefully at the upstream or downstream end of a spillway near the wall to determine if it is tilting inward or outward. A fence on top of the retaining wall is sometimes erected in a straight line at the time of construction; therefore, any curve or distortion of the fence line may indicate wall deformation. Misalignment or displacement of walls is often accompanied by cracks.
Misalignment/ movement of adjacent slabs	• Stability failure due to uplift • Stability failure due to sliding • Structural failure due to excessive uplift pressure • Structural failure due to undermining	See **Figure 6.14**
Movement of surrounding land adjacent to spillway	• Structural failure due to loss of side support and undermining	Warning signs in an embankment include sloughing, sliding, depressions, bulging, scarps
Random wall drains not discharging	• Stability failure due to uplift • Stability failure due to sliding • Structural failure due to excessive uplift pressure • Structural failure due to loss of side support and undermining	See **Figure 6.15**
Sediment discharging from drain	• Stability failure due to uplift • Stability failure due to sliding • Structural failure due to excessive uplift pressure • Structural failure due to undermining	See **Figure 6.16**

Figure 6.1 Cracking of concrete slabs (Source: Jeremy Young)

Figure 6.2 Partially blocked drain (Source: Paul G Schweiger)

Figure 6.3 Concrete spall (Source: California Department of Water Resources

Figure 6.4 Exposed reinforcement (Source: Paul G Schweiger)

Figure 6.5 Damaged joint sealant (Source: Paul G Schweiger)

Figure 6.6 An open joint (Source: Paul G Schweiger)

Figure 6.7 Vegetation growing on the spillway (Source: Paul G Schweiger)

Figure 6.8 Increased discharge from drains (Source: Kelly M Grow, California Department of Water Resources, 2017)

Figure 6.9 Edge of the downstream concrete slab is exposed and higher than the upstream slab at the transverse joint (Source: Jeremy Young)

Figure 6.10 Seepage in the conveyance channel (Source: Canal & River Trust)

Figure 6.11 Ice coverage on the downstream spillway face identifying seepage locations January 2011 (Source: Dŵr Cymru Welsh Water, 2017)

Figure 6.12 Leakage from a spillway joint (Source: California Department of Water Resources)

Figure 6.13 wet/ damp areas on embankment alongside spillway (Source: Canal & River Trust)

Figure 6.14 Adjacent slab is lower (Source: Jeremy Young)

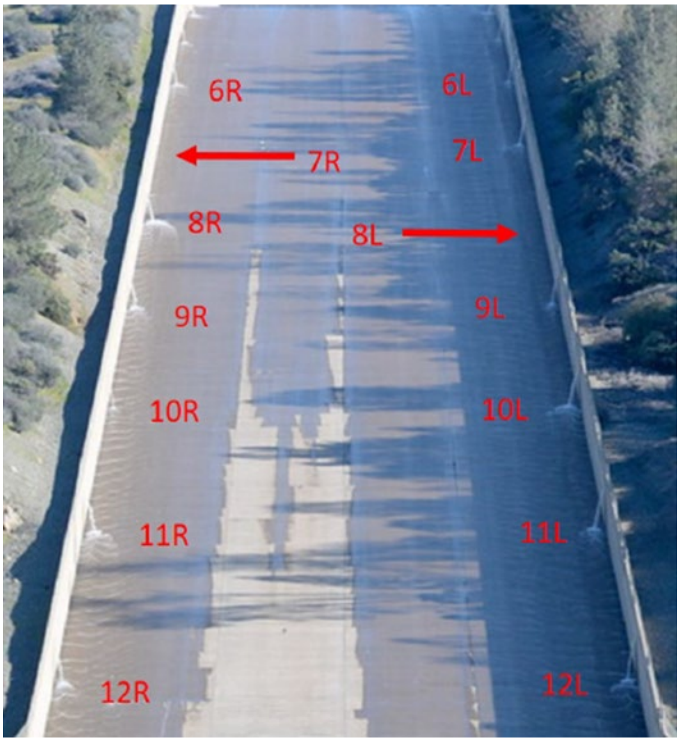


Figure 6.15 Not all drains are discharging along the retaining walls (Source: California Department of Water Resources)

Figure 6.16 Discharge from drain containing sediment (Source: Jeremy Young)

Table 6.3: Visual warning signs when the spillway is operating

Visual warning signs	Potential failure mechanisms	Illustrations/practices to spot signs
Apparent dry areas of the conveyance channel	• Stability failure due to uplift • Stability failure due to sliding • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to corrosion of reinforcement	See **Figure 6.17**
Discoloured discharge	• Stability failure due to uplift • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to excessive cracking and corrosion of reinforcement	See **Figure 6.18**
Emerging seepage from joints	• Stability failure due to uplift • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to corrosion of reinforcement	See Figure 6.19
Flow disturbance	• Structural failure due to excessive uplift pressure • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to excessive cracking and corrosion of reinforcement •	See Figure 6.20
Leakage/ seepage near to the spillway	• Structural failure due to loss of side support and undermining	See **Figure 6.13** for an example of a wet/ damp area alongside spillway

Figure 6.17 Water flow is not continuous down the spillway (Source: Jeremy Young)

Figure 6.18 Parts of spillway flow is discoloured (Source: Kelly M Grow, California Department of Water

Resources, 2017)

Figure 6.19 Emerging seepage from joints (Source: Paul G Schweiger)

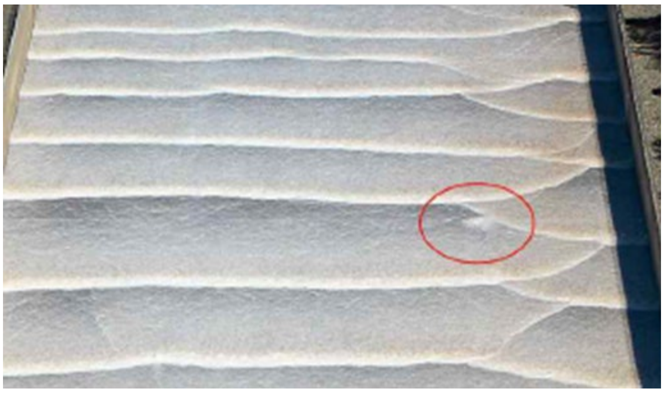


Figure 6.20 Flow disturbance (circled) when spillway operates (Source: Source: Kelly M Grow, California Department of Water Resources, 2017)

Figure 6.1 Cracking of concrete slabs (Source: Jeremy Young)

Figure 6.2 Partially blocked drain (Source: Paul G Schweiger)

Figure 6.3 Concrete spall (Source: California Department of Water Resources

Figure 6.4 Exposed reinforcement (Source: Paul G Schweiger)

Figure 6.5 Damaged joint sealant (Source: Paul G Schweiger)

Figure 6.6 An open joint (Source: Paul G Schweiger)

Figure 6.7 Vegetation growing on the spillway (Source: Paul G Schweiger)

Figure 6.8 Increased discharge from drains (Source: Kelly M Grow, California Department of Water Resources, 2017)

Figure 6.9 Edge of the downstream concrete slab is exposed and higher than the upstream slab at the transverse joint (Source: Jeremy Young)

Figure 6.10 Seepage in the conveyance channel (Source: Canal & River Trust)

Figure 6.11 Ice coverage on the downstream spillway face identifying seepage locations January 2011 (Source: Dŵr Cymru Welsh Water, 2017)

Figure 6.12 Leakage from a spillway joint (Source: California Department of Water Resources)

Figure 6.13 wet/ damp areas on embankment alongside spillway (Source: Canal & River Trust)

Figure 6.14 Adjacent slab is lower (Source: Jeremy Young)

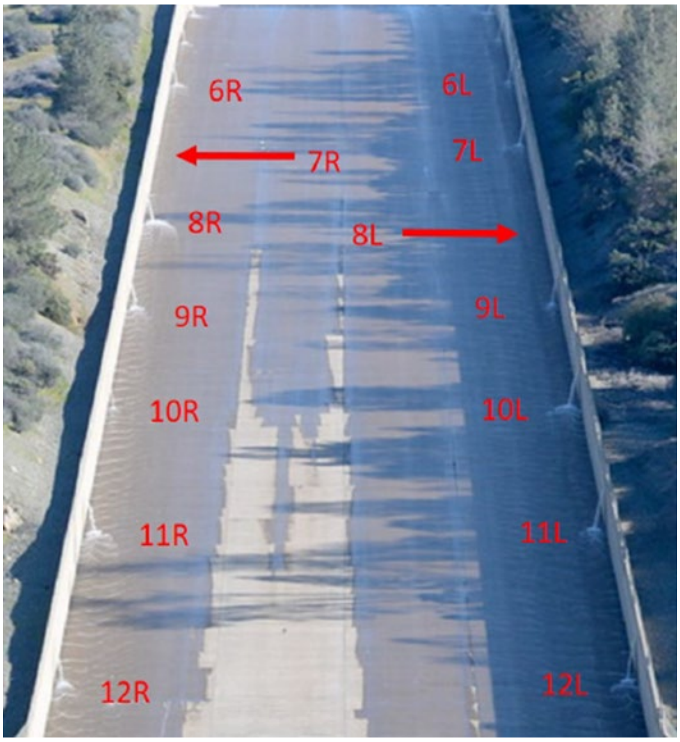


Figure 6.15 Not all drains are discharging along the retaining walls (Source: California Department of Water Resources)

Figure 6.16 Discharge from drain containing sediment (Source: Jeremy Young)

Table 6.3: Visual warning signs when the spillway is operating

Visual warning signs	Potential Failure Mechanisms	Illustration/ Description of Sign
Apparent dry areas of the conveyance channel	• Stability failure due to uplift • Stability failure due to sliding • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to corrosion of reinforcement	See **Figure 6.17**
Discoloured discharge	• Stability failure due to uplift • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to excessive cracking and corrosion of reinforcement	See **Figure 6.18**
Emerging seepage from joints	• Stability failure due to uplift • Structural failure due to excessive uplift pressure • Structural failure due to undermining • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to corrosion of reinforcement	See Figure 6.19
Flow disturbance	• Structural failure due to excessive uplift pressure • Structural failure due to excessive unaccounted dynamic actions • Structural failure due to excessive cracking and corrosion of reinforcement	See Figure 6.20
Leakage/ seepage near to the spillway	• Structural failure due to loss of side support and undermining	See **Figure 6.13** for an example of a wet/ damp area alongside spillway

Figure 6.17 Water flow is not continuous down the spillway (Source: Jeremy Young)

Figure 6.18 Parts of spillway flow is discoloured (Source: Kelly M Grow, California Department of Water

Resources, 2017)

Figure 6.19 Emerging seepage from joints (Source: Paul G Schweiger)

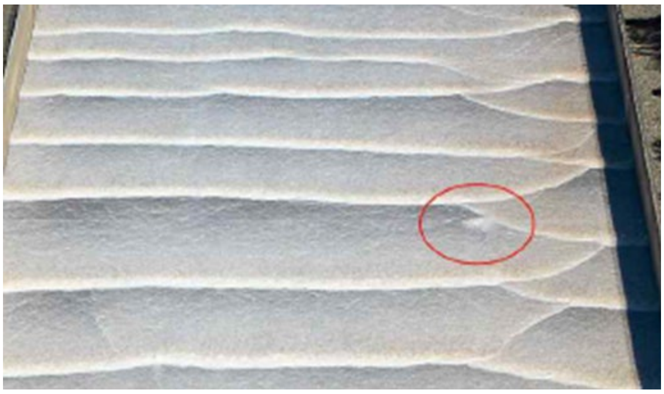


Figure 6.20 Flow disturbance (circled) when spillway operates (Source: Source: Kelly M Grow, California Department of Water Resources, 2017)

7. Techniques for Investigating Vulnerabilities

7.1. Overview

This chapter provides some insights into available and emerging techniques to investigate concrete spillway vulnerabilities that often influence potential failure mechanisms. It also contains information on developing an investigation strategy and how to improve the quality of findings. An investigation strategy is widely accepted as best practice; some benefits are covered in section 7.2.

The need to create an investigation strategy will originate from the inspection report and addressing measures in the interests of safety. It is anticipated that the insights will enable targeted work and improve decision-making by the reservoir manager/undertaker and appointed qualified civil engineer when addressing measures in the interests of safety. If a supervising engineer is in any doubt, they should have a conversation with an inspecting engineer, ideally the one who completed the last inspection.

A range of techniques are presented that were known when the research was completed in 2021. Some of them can also improve the understanding on the spillway details and provide information on the general condition of the spillway. Anyone considering the use of the techniques are advised to carry out their own searches to identify any updates or ones that have become available since the research was completed.

The chapter is separated into:

- considerations for developing an investigation strategy (Section 7.2)
- techniques for detecting voids (Section 7.3)
- techniques for detecting flow paths and seepage (Section 7.4)
- techniques for confirming design features and concrete condition (Section 7.5)
- a selection of emerging techniques (Section 7.6)

Supplementary information and case studies are contained in Appendix F.

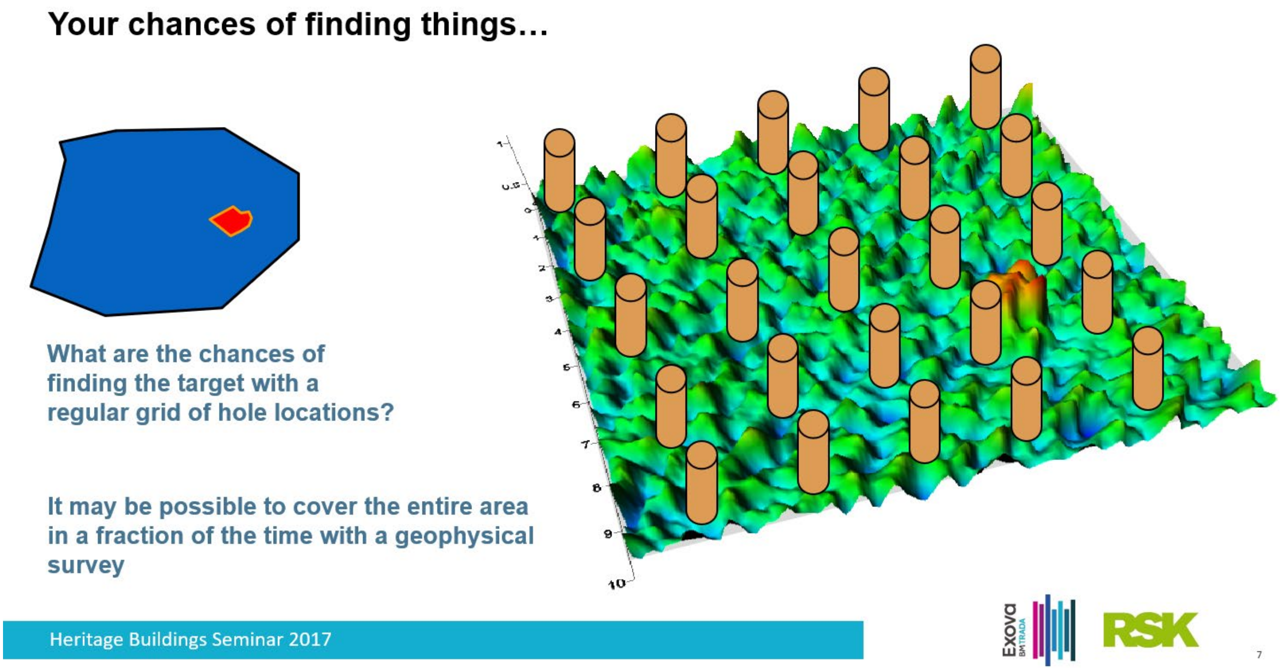
7.2. Developing an investigation strategy

7.2.1 Reasons for developing an investigation strategy

Creating an investigation strategy can help detect problems sooner and make investigations more cost-effective. For example, choosing to perform certain non-destructive[17] surveys before using intrusive[18] techniques can realise significant benefits such as:

- enabling site characterisation
- increasing the chances of discovering a problem, as illustrated by **Figure 7.1**
- indicating the extent of a problem
- enabling targeted intrusive investigation
- minimising the cost of intrusive investigations
- avoiding abortive investigations

According to several global publications[19], a combination of techniques is necessary to accurately understand and reliably corroborate findings. Developing an investigation strategy can help select appropriate techniques in order to improve the accuracy and validity of anomalies.



[17] Sometimes known as ‘reconnaissance investigations’, non-destructive or non-invasive evaluations are where the structure’s integrity remains intact.

[18] Where the structure is cut open or excavated to see the subsurface, resulting in partial, temporary damage.

[19] Adamo and others (2020b); Hsu and others (2019); Park (2018); Zumar and others (2018); Young (2010); Sack and others (2008); CIRIA (2002).

Figure 7.1: Illustration showing disadvantages of using a grid of invasive sampling without deploying non-destructive 'reconnaissance' techniques (RSK presentation at Heritage Buildings Seminar 2017).

7.2.2 Considerations when developing an investigation strategy

The following recommended approach and considerations for developing an investigation strategy build upon CIRIA (2002), Park (2018) and industry insights.

1. Define the investigation objectives – what vulnerabilities need to be explored and assessed.
2. Define the area of investigation – this may influence suitability of techniques. Ideally cover a larger area than the visual warning signs as the reasons could be more extensive.
3. Decide whether to use non-intrusive survey initially – there are generally more benefits to using non-intrusive 'reconnaissance' first, but there might be times when there is an urgency to use intrusive methods.
4. **Table 7.1**, **Table 7.2**, and **Table 7.3** provide a starting point to understand the limitations and precision of techniques. It is worthwhile having early consultation with specialists[20] to offer further insights on suitable techniques that can corroborate findings.
5. Use 2 or more techniques – relying on one technique can provide only qualitative understandings. Using techniques together will reduce the uncertainty significantly when interpreting results.
6. Decide on the procurement/selection criteria of specialists – the quality of investigations is significantly affected by the competence and experience of operators and specialists. The following considerations will increase the quality of proposals and investigation outputs:
    a. Weighting the selection criteria towards quality. For example, it is common in the flood and coastal erosion risk management community to use 60:40 or 70:30 for quality-cost evaluations.
    b. Understanding the qualifications, accreditations and experience of specialists. The distinction between operators of equipment and geophysical consultants/engineers is sometimes blurred in this sector, therefore it is important to check competencies. A good indication is that the specialist is chartered with a relevant professional body. Asking for past client references and contacting them can improve confidence in the competence of specialists.

[20] This covers geophysical and/or structural consultants, engineers and contractors.

c. Setting a minimum scope to cover important activities. This also helps in evaluating tenders. Examples of activities that will improve the quality of findings are:
    I. a site visit prior to any investigations. This will also inform the management of health and safety
    II. scrutinising spillway and dam information – having a better understanding of the construction will help the choice of investigation techniques and the detection of design vulnerabilities. Date of construction, as-built drawings, construction photographs, geotechnical design, historical cores, concrete mix designs, cube tests results and previous inspection records will strengthen an investigator's knowledge
    III. a trial of the potential method(s) prior to performing the full investigation. This can help minimise inducing instability issues as well as improving health and safety of operatives
    IV. production of an interpretation report. In addition to presenting the analysis of the survey, it should describe the reasons for techniques selected, their accuracy and limitations, and any calibrations
    V. undertaking a risk assessment. This should identify health and safety hazards and explain how they will be avoided or mitigated before and during investigations and who is responsible
    VI. quality assurance management. The quality of results of some non-intrusive techniques are affected by the presence of vegetation and condition of the ground. Evidence should be provided on how the quality of work will be managed and checked. A formal certification by an outside registration body can provide some reassurance but does not necessarily guarantee that practices are widespread
    VII. timely and transparent communications. It is good practice to allow for 2 meetings. The first is commonly known as a 'kick off' meeting to confirm and clarify the scope and schedule; this can minimise surprises later. The second meeting could take place after issuing the draft investigation report to explain findings and any uncertainties. These meetings could be online to minimise costs and impacts of travel

Further guidance on planning an investigation is located in CIRIA's 2002 C562 report and will be superseded by its publication 'Non-destructive testing of civil structures' (RP1081). Appendix F1 provides an overview of the typical stages of a non-intrusive survey. Appendix F2 presents the standard stages of an intrusive investigation.

7.3. Techniques for detecting voids

Table 7.1 provides benefits and insights on a range of techniques to detect voids directly beneath concrete slabs. The techniques are ordered alphabetically and according to the speed of capture (time to see results). Brief details are given on the theory/mechanics of each technique. For further details on the techniques, a list of publications is provided in section 7.7

Table 7.1: A selection of techniques to detect voids directly beneath concrete slabs

Technique	Benefits	Insights and limitations	Speed
Non-destructive techniques (NDT)			
Borescope investigation camera	• Quick to set up and simple to use • Camera is small enough to fit into existing holes/open joints • Can record footage	• Difficult to quantify extent of void from imagery • High resolution is possible and with a long reach. Water industry has extensive experience to investigate sewers • Larger systems can be used down boreholes • Requires close, direct access, that is, within touching distance	Relatively fast
Chain survey	• Simple, inexpensive equipment • Instant results (no data processing)	• Can help to indicate where to perform more sophisticated techniques • Experience required • Qualitative results – no details on depth or size of void • Requires close, direct access, that is, within touching distance	Relatively fast
Ground Penetrating Radar (commonly known as GPR. An electro-magnetic method)	• Offers full continuous coverage relatively rapidly across a surface compared to a single point provided by a core sample • Not limited by gradients as long as surface can be accessed safely • Outputs can be presented in a variety of ways • Can also gather information on construction details (for example, rebar) • Can assess a change in structure's condition when performed frequently as a monitoring tool (**Chapter 8**)	• Required depth defines the frequency. Best to use antenna arrays with minimum dual frequency (typically 400 to 1500MHz for void detection) • If reinforcement is not too densely spaced, can detect anomalies up to 2m below the surface • Equipment must be flush to the ground surface. Any air gap between the ground and the GPR antenna will result in signal attenuation • Require calibration/validation for accurate depth readings. Depth accuracy typically 15-20% without calibration and 10% or better with calibration (using cores or drill holes) • Water content limits degree of radar penetration • Requires close, direct access, that is, within touching distance • Quick data acquisition but processing can be slow	Relatively fast
Infrared thermography (commonly known as IRT)	• Able to detect small variations in temperature, which indicate voiding, delamination or moisture • No access is required; data can be obtained remotely • Often real-time displays	• Highly weather-dependent • Limited depth of penetration, so best to combine with other methods • Requires specialist equipment (hardware and software), training and experience	Relatively fast
Impact Echo (commonly known as IE)	• Can identify concrete thickness • Can estimate concrete strength alongside core	• Field data acquired quickly but at individual points, so can be relatively slow to cover a large area • Limited to up to 700mm depths	Relatively moderate

	sampling and compressive strength testing • Can indicate presence of delamination and internal cracking • Not affected by presence of reinforcement steel	• Single-sided access to the spillway slab limits the survey techniques to the ‘indirect method’ so best to combine with other methods, for example, GPR • Requires close, direct access, that is, within touching distance • Requires specialist equipment (hardware and software), training and experience	
Destructive/intrusive techniques			
Boreholes and down-hole void scanning	• Allows quantification and visualisation of void spaces (using CCTV cameras and laser scanning) • Can establish features and ground conditions underneath • Range of methods available to create hole, for example, diamond coring, Dynamic Cone Penetrometer, dynamic probing, dynamic sampling, percussion and rotary coring • Range of rigs available to suit restricted access and gradients, including hand-held, modular and slope climbing drilling rigs	• Allows installation of monitoring instrumentation • Provides greater depth of investigations to other techniques • Represents only a narrow window of investigation (generally up to 150mm diameter) • Requires due care in terms of creating preferential pathways, and ensuring the level of reinstatement does not create weaknesses and pathways • Chosen drilling technique requires careful planning to ensure that the investigation does not induce instability, for example, rotary drilling flush • Boreholes need to be unlined in area of interest to ensure void is visible • Requires close, direct access, that is, within touching distance	Relatively slow
Sonic tomography (sometimes referred to as crosshole seismics)	• Can detect larger voids in in the subsurface • In concrete/masonry dams with excessive seepage/ leakage, sonic tomography can help identify permeable zones, cracks, voids and cavities. This information can help to define the grouting pattern/details for control of seepage	• Deployed in boreholes below the ground • Provides information on the distribution of the elastic properties of the subsurface between boreholes	Relatively slow

7.4. Techniques for detecting flow paths and seepage

Table 7.2 provides benefits and insights on a range of techniques to detect flow paths and seepage. The techniques are ordered alphabetically and according to the speed of capture (time to see results). Brief details are given on the theory/ mechanics of each technique. For further details on the techniques, a list of publications are provided in section 7.7. Appendix F4 contains a case study to investigate seepage and determine slab construction.

Table 7.2: A selection of techniques to detect flow paths and seepage

Technique	Benefits	Insights and limitations	Speed
Non-destructive techniques (NDT)			
Borescope investigation camera	• Quick to set up and simple to use • Camera is small enough to fit into existing holes/open joints • Can record footage	• Difficult to quantify extent of void from imagery • High resolution is possible and with a long reach. Water industry has extensive experience to investigate sewers • Larger systems can be used down boreholes • Requires close, direct access, that is, within touching distance	Relatively fast
Dye test (sometimes referred to as tracer test)	• Simple, inexpensive technique (sandbagging an area where visible seepage occurs, flooding area with food grade colour dye and water to witness flow paths and emergence elsewhere) • Instant results (no data processing)	• Qualitative results – no digital outputs showing location of flow paths • Can help to indicate where to perform more sophisticated techniques or carry out intrusive techniques • Requires close, direct access, that is, within touching distance	Relatively fast
Ground Penetrating Radar (commonly known as GPR. An electro-magnetic method)	• Offers full continuous coverage relatively rapidly across a surface compared to a single point provided by a core sample • Not limited by gradients as long as surface can be accessed safely • Outputs can be presented in a variety of ways • Can also detect historic structures, buried services, construction details and a structure's condition • If reinforcement is not too densely spaced, can detect anomalies up to 2m below the surface	• Required depth defines the frequency. Best to use antenna arrays with minimum dual frequency (typically 400 to 1500MHz for void detection) • Suitable for materials of >100Ωm resistivity. Clay rich material can attenuate the GPR signal at mid-frequency (400MHz), so the investigation depth may be restricted • Equipment must be flush to the ground surface. Any air gap between the ground and the GPR antenna will result in signal attenuation • Require calibration/validation for accurate depth readings. Depth accuracy typically 15-20% without calibration and 10% or better with calibration (using cores or drill holes). Water content limits degree of radar penetration • Requires close, direct access, that is, within touching distance • Quick data acquisition but processing can be slow	Relatively fast
Infrared thermography (commonly known as IRT)	• Able to detect small variations in temperature, which can indicate seepage • No access is required; data can be obtained remotely	• Highly weather-dependent • Limited depth of penetration, so best to combine with other methods • Requires specialist equipment (hardware and software), training and experience	Relatively fast
Electrical resistivity tomography (commonly	• Can detect wet spots • Can indicate geological strata and depth of bedrock	• Captures data along a profile, so only continuous along a single line • Moderate time to acquire data (approx. 2 lines per day)	Relatively moderate

Technique	Benefits	Insights and limitations	Speed
known as ERT and sometimes referred to as an electrical method)	• Can identify preferential fluid pathways and map moisture	• Preferably to be deployed on soft standing ground otherwise probe holes need to be drilled – but electrodes do require access to underlying soils • The maximum depth of penetration is a factor of the linear length of the profile. This is dependent on electrode spacing. Typically, a 2m spaced electrode array enables a maximum depth of 20mbgl at the centre of an 142m array. Whereas a 0.5m spaced electrode array enables maximum depth of 8mbgl at the centre of a 35m long array • Unsuitable on gradients greater than 45 degrees Requires close, direct access, that is, within touching distance	
Self-potential imaging (commonly known as SP and sometimes referred to as an electrical method)	• Can identify preferential fluid pathways and map moisture • Can also detect leaks in a dam • Raw data requires little processing as most interpretations are based on qualitative analysis of profile, shape, polarity and amplitude	• Self-potentials are measurements of the difference in natural electrical potentials between 2 points on the ground surface and may be generated by groundwater flow • Data is collected along a survey line (SP profiling), or across a grid to produce a contour map of self-potential • Depth of results is dependent on electrode spacing • The technique is very susceptible to sources of external electrical 'noise' • Requires close, direct access, that is, within touching distance	Relatively moderate
Magnetometric survey (commonly known as the Willowstick method)	• Models (predicts/infers) a qualitative distribution of hydraulic conductivity in the subsurface at depths up to 300m using magnetic field measurements • 2D maps and 3D models are generated • Uses 3D models to predict future behaviour based on trends, trajectory, and timing • Data is processed overnight	• Electrodes must be placed in direct contact with water upstream and downstream • Require proprietary instrument to collect readings from the magnetic field (induced by an electric circuit) • Grid resolution of 20m to 0.5m • Require proprietary inversion algorithms to render 3D models of subsurface groundwater flow patterns • Proprietary filtering algorithms filter interference from man-made conductive culture • Require other hydrogeologic data to provide an enhanced definition of preferential groundwater flow paths	Relatively moderate
GroundSat Analysis	• No access is required; data is obtained remotely via satellite • Large areas are covered • Relative soil moisture mapping • Data capture is unaffected by weather or rain • The L-Band SAR can penetrate concrete	• Technique using ASTERRA EarthWorks high resolution soil moisture mapping • Uses satellite-borne L-Band Synthetic Aperture Radar (SAR) sensor with a 3-6m horizontal resolution • Data acquisition takes 2-3 week and analysis takes a further 2 weeks • May provide insights into subsurface (<1m) flow paths and piping, especially when supplemented by other techniques	Relatively slow

Technique	Benefits	Insights and limitations	Speed
		• See section 7.6 for more details	
Destructive/ intrusive methods			
Boreholes and down-hole void scanning	• Allows quantification and visualisation of void spaces • Can establish features and ground conditions underneath • Range of methods available to create hole, for example, diamond coring, Dynamic Cone Penetrometer, dynamic probing, dynamic sampling, percussion and rotary coring • Range of rigs available to suit restricted access and gradients including hand-held, modular and slope climbing drilling rigs	• Allows installation of monitoring instrumentation • Provides greater depth of investigations to other techniques • Represents only a narrow window of investigation (generally up to 150mm diameter) • Require due care in terms of creating preferential pathways, and ensuring the level of reinstatement does not create weaknesses and pathways • Chosen drilling technique requires careful planning to ensure that the investigation does not induce instability, for example, rotary drilling flush Requires close, direct access, that is, within touching distance	Relatively slow
Trial hole excavations	• Direct confirmation of water penetration through structure and design vulnerabilities, for example, missing waterstops	• To minimise the destruction area and/or focus the target area of intrusive investigations, use a non-intrusive technique initially, for example, GPR/IRT can identify potential damage zones • Requires close, direct access, that is, within touching distance	Relatively slow

7.5. Techniques for confirming design features or concrete condition

Table 7.3 provides benefits and insights on a range of techniques to confirm structural design aspects and concrete condition. The techniques are ordered alphabetically and according to the speed of capture (time to see results). Brief details are given on the theory/ mechanics of each technique. For further details on the techniques, a list of publications is provided in section 7.7.

Table 7.3: A selection of techniques to confirm design features or concrete condition

Technique	Benefits	Insights and limitations	Speed
Non-destructive techniques (NDT)			
Ground Penetrating Radar (commonly known as GPR. An electro-magnetic method)	• Offers full continuous coverage relatively rapidly across a surface compared to a single point provided by a core sample • Not limited by gradients as long as surface can be accessed safely • Outputs can be presented in a variety of ways that are relatively easy to interpret • Imaging can indicate reinforcement arrangement and thickness of concrete • Can assess a change in structure's condition when performed frequently as a monitoring tool (**Chapter 8**)	• Required depth defines the frequency. Best to use antenna arrays with minimum dual frequency (typically 900 to 2,600MHz for concrete evaluation) • Equipment must be flush to the ground surface. Any air gap between the ground and the GPR antenna will result in signal attenuation • Require calibration/validation for accurate depth readings. Depth accuracy typically 15-20% without calibration and 10% or better with calibration (using cores or drill holes). Water content limits degree of radar penetration • Requires close, direct access, that is, within touching distance • Quick data acquisition but processing can be slow	Relatively fast
Transient pulse thermography (commonly known as TPT)	• External heating source can be optimised to suit conditions • Able to quickly cover large surfaces without close access • Equipment (camera) is easily portable and visualises sub-surface defects	• Highly weather-dependent • Infrared emission depends the surface emissivity • Limited depth of penetration; require other methods to validate results • Requires specialist equipment (hardware and software), training and experience	Relatively fast
Rebar scanning and cover meters	• Useful evaluation on structures with unknown design features • Corrosivity analysis is available	• Limited depth penetration • Needs to be perpendicular to the surface and relatively flat surfaces are required • Requires close, direct access, that is, within touching distance	Relatively moderate
Impact Echo (commonly known as IE)	• Can estimate concrete strength alongside core sampling and compressive strength testing • More sophisticated than ultrasonic techniques • Not affected by presence of reinforcement steel	• Field data acquired quickly but at individual points, so can be relatively slow to cover large area • Single-sided access to the spillway slab limits the survey techniques to the 'indirect method' • Limited to up to 700mm depths • Requires close, direct access, that is, within touching distance • Requires specialist equipment (hardware and software), training and experience	Relatively moderate

Technique	Benefits	Insights and limitations	Speed
Rebound hammer (also known as Schmidt hammer)	• Surface hardness measurements can be used to estimate concrete strength, in accordance with BS EN 12504-2	• Not reliable as an indicator of concrete strength when used as a standalone technique. Recommend coupling with ultrasonic pulse velocity, Impact Echo or concrete sampling and compressive strength testing • Requires close, direct access, that is, within touching distance • Cores are essential for calibration purposes	Relatively slow
Ultrasonic pulse velocity (commonly known as UPV)	• Can identify variations in condition and voids within concrete slab • Can be used to estimate concrete strength alongside core sampling and compressive strength testing as per BS EN 13791:2019	• Requires specialist equipment (hardware and software), training and experience • Single-sided access to the spillway slab limits the survey techniques to the 'indirect method' (as per BS EN 12504-4:2004), which has lower confidence in compressive strength estimate results • Requires close, direct access, that is, within touching distance • Cores are essential for calibration purposes	Relatively slow
Destructive/ intrusive methods			
Diamond coring	• Obtains core samples for laboratory testing, for example, petrographic analysis • Accurately identifies materials and condition • Forms a hole for further investigation techniques, for example, borescope investigation camera, probing.	• Small diameter cores may not be representative; adequate number of cores required • Cored holes must be adequately reinstated to prevent preferential pathways/ leakage • Requires close, direct access, that is, within touching distance	Relatively slow
Boreholes and down-hole void scanning	• Allows quantification and visualisation of void spaces (using CCTV cameras and laser scanning) • Can establish features and ground conditions underneath • Range of methods available to create hole, for example, diamond coring, Dynamic Cone Penetrometer, dynamic probing, dynamic sampling, percussion and rotary coring • Range of rigs available to suit restricted access and gradients including hand-held, modular and slope climbing drilling rigs	• Allows installation of monitoring instrumentation • Provides greater depth of investigations to other techniques • Represents only a narrow window of investigation (generally up to 150mm diameter) • Require due care in terms of creating preferential pathways, and ensuring the level of reinstatement does not create weaknesses and pathways • Chosen drilling technique requires careful planning to ensure that the investigation does not induce instability, for example, rotary drilling flush • Boreholes need to be unlined in area of interest to ensure void is visible • Requires close, direct access, that is, within touching distance	Relatively slow

7.6. A selection of emerging techniques

7.6.1 GroundSat Analysis

GroundSat analysis is a technique using ASTERRA EarthWorks high resolution soil moisture mapping, which is a patented method of analysing images captured by a satellite-borne[21] L-Band Synthetic Aperture Radar (SAR) sensor with a 3m to 6m horizontal resolution. This should not be confused with commercial or open access InSAR. The ASTERRA EarthWorks technique has been adapted from earlier academic projects that searched for water on other planets, and more recently from leakage detection in the utility sector.

The use of satellite microwave remote sensing technologies for quantitative soil moisture mapping was introduced in the 1980s with SAR technology. This method was applied and proven to be accurate in the upper soil layer, that is, at 5 to 10 cm depth (Behari, 2005). Initially, there were weaknesses regarding spatial resolution, soil texture, surface roughness and vegetation coverage. The use of full (Quad) polarimetry SAR imagery (with L-band) has significantly improved the accuracy of the results as it can penetrate both vegetation and the topsoil layer (typically <1m). This has been demonstrated by ASTERRA and Central Alliance as well as other world authorities on the technique[22]. The studies show that backscatter data provides a high correlation with gravimetric measurements on field soil samples.

GroundSat helps assess relative soil moisture values beneath the surface, including concrete and could assist seepage investigations at spillways. Figure 7.2 shows 3 images of soil moisture data as a percentage at a reservoir earth dam and concrete spillway. The left image shows the soil moisture content pixels for the whole area ranging from 10% to 60%. The other images show smaller ranges to show wetter areas more easily.

[21] from either ALOS-2 or SAOCOM satellites.

[22] Ponganan, and others, 2016: Sekertekin, Marangoz, Abdikan & Esetlili, 2016.

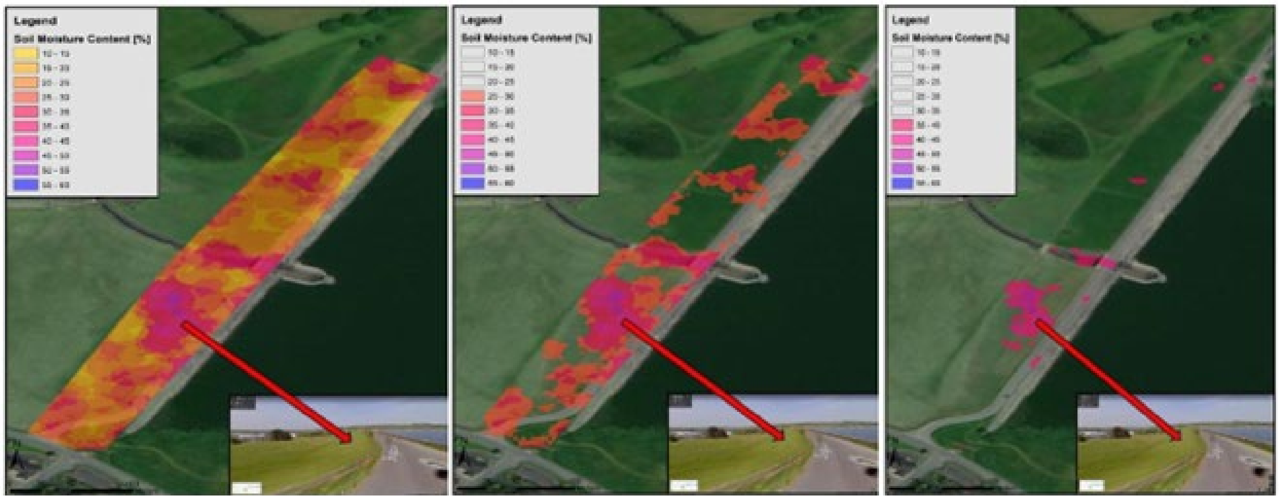


Figure 7.2: Illustration of soil moisture mapping data (colour contours) at an earth dam and concrete spillway (photograph courtesy of ASTERRA)

7.6.2 Muon tomography

Muon tomography provides non-invasive, non-destructive imaging of material density under, over or to the side an object of interest. This includes the identification and characterisation of hidden voids, which could be useful for dams and spillways. The first application of muon tomography determined the overburden to the side of a tunnel system at a hydroelectric power station.

Cosmic ray muons are highly penetrating, with significant fluxes capable of passing through hundreds of metres of rock and soil overburden. The principle of muon tomography has been around for a while and successfully applied to the imaging of Egyptian pyramids[23], nuclear reactors[24], volcanoes[25] and underground tunnels[26].

Recently, muon tomography has come to the fore for commercial applications to assist short-term asset inspection and investigations. Thompson and others (2020) used muon tomography techniques for infrastructure applications, locating and imaging hidden tunnel shafts in railway tunnels. The portability of cosmic ray muon radiography was an ideal imaging system that met the strict timing requirements for working in live railway tunnels.

Muon tomography monitoring is being developed to detect long-term change in over-burden, for example, changes due to water ingress. This could provide early warning of

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[23] Alvarez and others (1970); and Morishima and others (2017).

[24] Miyadera and others (2013).

[25] Tanaka and others (2014).

[26] Guardincerri and others (2017).

spillway vulnerabilities and avoid potential catastrophic events. Additionally, borehole detectors are being developed that could provide further methods to introduce detectors below and to one side of dam spillways, allowing a more comprehensive investigation.

7.6.3 Cosmic ray neuron sensors

Cosmic ray soil moisture sensors (Figure 7.3) have been developed to monitor changing soil moisture at a specific area over time. This method of real-time monitoring could provide insights into changing sub-surface soil moisture and provide early warning of spillway vulnerabilities. One detector, in principle, is sensitive to water content up to 200m from its deployment site and the water content sensitivity is down to approximately 30cm in depth. This technique requires further evaluation prior to implementation.

Figure 7.3: A cosmic ray soil moisture sensor (Photograph courtesy of Geoptic/ Central Alliance)

7.7. Further reading

For more detailed information on some of the techniques, here are a few useful publications in chronological order:

- CIRIA (unpublished) Non-destructive testing of civil structures. Report RP1081 by Mckibbins L, Abbott T, Atkins C, Moss E, Wright D: Chapter 4 covers techniques, methods and application. Chapter 6 covers developing an investigation strategy and procurement. Appendix B provides one-page summaries on 31 techniques.
- CENTRAL WATER COMMISSION, 2020. Manual for Assessing Structural Safety of Existing Dams. November 2020. CDSO_MAN_DS_03_v1.0 https://damsafety.in/ : Chapter 4 (p53-59) covers many investigations in detail with general tests for concrete/masonry dams (p54-56).

- RSK, 2020. A Reference for Geophysical Techniques and Applications, 4th Edition: Useful illustrations of most techniques (equipment and survey outputs).
- PARK, C., 2018. Geophysical methods for reservoir safety investigations. Commissioned by the Environment Agency and British Dam Society: covers methods for earth embankments. Reproduces figures from RSK Geophys Handbook.
- INTERNATIONAL ATOMIC ENERGY AGENCY, 2017. Cosmic Ray Neutron Sensing: Use, Calibration and Validation for Soil Moisture Estimation, IAEA-TECDOC-1809, IAEA, Vienna.
- HSU, K.T., CHENG, C.C., CHIANG, C.H., 2017. Assessing the integrity of spillway foundations, AIP Conference Proceedings: case study using GPR to check for voids under a spillway.
- CIRIA, 2015. Dam and reservoir conduits. Inspection, monitoring, maintenance and repair (C743). Report C743 by Hughes A. K., Bruggemann D. A., Gardiner K. D., Blower T., Deane M., Nash D. F. T. Chapter 5 describes several techniques and examples of where they have been applied, including Willowstick (section 5.3.4, p52).

8. Techniques for Monitoring

8.1. Overview

This chapter aims to help:

1. inspecting engineers give guidance on what to monitor at spillways
2. supervising engineers advise the reservoir manager/undertaker to carry out additional monitoring when they have a concern at the spillway
3. reservoir managers'/undertakers' staff gain more insights when appraising potential monitoring techniques

The chapter has 6 elements:

- Philosophy of monitoring (section 8.2)
- A summary of techniques to detect change (section 8.3)
- Techniques to detect changes in cracks (section 8.4)
- Techniques to detect changes in movement (section 8.5)
- Techniques to detect changes in seepage (section 8.6)
- Further reading (section 8.7)

The chapter contains information on a range of techniques that were known when the research was completed in 2021. Anyone considering the use of the techniques are advised to undertake their own searches to identify any updates or ones that have become available since the research was completed.

Supplementary information and case studies are contained in Appendix F.

8.2. Philosophy of monitoring

Alongside visual inspections (Chapter 6) and investigations (Chapter 7), monitoring[27] forms an integral part of dam safety to detect early indicators of adverse performance. Monitoring should always supplement visual observations and never substitute regular visual surveillance.

There are many good resources on what is required to have a successful monitoring system; section 8.7 contains a selection. The most important aspects to remember are that:

- monitoring is most useful when it is:
    - linked to potential failure mechanisms (section 3.3)

    - undertaken repeatedly and at specific intervals and locations
    - part of a suitable warning system with clear procedures for taking appropriate action (remedial or emergency response)
    - regularly calibrated and is easy to record

- instrumentation and monitoring should be carefully planned and executed to meet defined objectives and purpose. The more data recorded, the easier to spot sudden changes
- understanding the limitations of the instrumentation (techniques) is just as important as knowing whether a trend is ‘normal’ or requires action. It is advisable to create warning flags for instruments that trend oddly (not functioning properly)
- relate the readings to reservoir water level and rainfall to check if rates are constant or changing with time. Once a history of variation has been established with respect to season and reservoir level, then threshold parameter data can be established to trigger different actions. Software can enable quick interpretation
- monitoring can lead to an improved understanding of risks and therefore more targeted investment

With monitoring of spillways, a holistic view will provide insights when choosing monitoring techniques and evaluating data. This includes monitoring changes beyond the walls of the spillway. A good understanding of the likely mechanisms of behaviour is important as instruments can malfunction or give erroneous readings. It can also be helpful to consider past monitoring and the location of previous intrusive investigations.

8.3. A summary of techniques to detect change

8.3.1 Overview of the techniques

Table 8.1 presents a list of monitoring techniques for spillways and adjacent structures. It indicates the parameters that the technique monitors, such as existing cracks, movement or seepage. Where appropriate, further details on a technique and examples of specific uses are provided in a separate sub-sub-section.

Table 8.1 Summary of monitoring techniques for spillways

Technique	Cracks	Movement	Seepage	Specifically [28]	Further details
Crack gauge ruler	x			Spillway	Section 8.4.1
Demountable mechanical (demec) strain gauge	x			Spillway	Section 8.4.2
Plastic Tell-Tale gauge	x			Spillway	Section 8.4.3
Potentiometer	x			Spillway	Section 8.4.4
Thermal infra-red imagery	x			Spillway	Section 8.4.5
Vibrating wire strain gauge	x			Spillway	Section 8.4.6
Vernier caliper	x			Spillway	Section 8.4.7
Acoustic emissions		x		Soil slopes	Section 8.5.1
Photogrammetry via a drone		x		Whole dam	Section 8.5.2
Plastic displacement Tell-Tale gauge		x		Spillway	Section 8.5.3
Robotic total station		x		Whole dam	Section 8.5.4
Satellite imagery		x		Whole dam	Section 8.5.5
GPR			x	Spillway	Section 8.6.1
GroundSat			x	Whole dam	Section 8.6.2
Measurement container and stopwatch			x	Spillway	Section 8.6.3
Piezometer			x	Spillway	Section 8.6.4
V-notch weir			x	Spillway	Section 8.6.5
Water sampling			x	Spillway	Section 8.6.6

8.3.2 Emerging techniques discussion

There are a number of emerging methods and new technology that make use of developments, such as artificial intelligence and smart networks. Modern systems that constantly monitor can provide real time data via GSM networks and satellite communications along with data loggers. Some advantages of these smart systems include:

- can be programmed to send an 'alarm' to control rooms and/or specific personnel via emails and mobile phones
- have the potential to spot rapid deterioration or loss of spillway integrity, which can greatly improve warnings
- allow monitoring when inclement weather, such as snow, prevents personnel from attending site
- using cloud storage allows data to be reviewed and analysed remotely at any time from any location in the world

As modern methods are at different stages of development, it is important to check and understand the limitations before adopting them. For instance, remote-sensing should not be seen as the 'one size fits all solution'. It still needs human intervention to interpret the results, remove background 'noise' in the data and check that the system is working within its tolerances. It will however help guide inspections to check specific parts of the dam/spillway that may have been missed. It could also trigger a visual inspection earlier by the reservoir managers'/undertakers' staff or the supervising engineer.

While some modern methods promise short-term savings, the main consideration should be on longer term advantages and a reduction of risk. It can be helpful to produce an overall monitoring plan.

8.3.3 Non-instrumented approaches

It is important to mention a couple of approaches that do not require instrumentation – visual mapping and visual observations (FERC, 2020).

Visual mapping can be used to regularly record and check changes in seepage and wet areas. Using a map of the dam’s downstream profile, including the spillway, allows you to mark on any visible vertical joints, horizontal joint/lift lines, all cracks, leakage locations and seepage areas. Detailed photographs can supplement the approach. It is recommended that maps are created at the coolest and warmest times of the year and regularly compared, noting areas of increasing leakage flow or extension of cracks.

Visual observation can readily detect signs of poor performance (for example, offsets, misalignment, bulges) and variations or spatial patterns of such features. Visual observation should be made in conjunction with instrument monitoring. Photographs or videos can document existing conditions and help evaluate any changes. Visual observation at regular intervals by trained personnel will often detect unusual conditions, such as increased seepage, cloudy seepage, or movements.

8.4. Techniques to monitor cracks

8.4.1 Crack gauge ruler

A portable crack gauge ruler (Figure 8.1) can be used by inspecting staff to obtain a quick indication if a crack is starting to get wider. It can be used in the short term until a more permanent solution can be installed. Care must be taken to perform the reading at the same location each time; it is advisable that this location is permanently marked to allow a comparison.

Figure 8.1: Crack gauge ruler (Source: Richard Terrell, 2021)

8.4.2 Demountable mechanical (demec) strain gauge

This technique monitors crack width at a specific location. Once stainless-steel plates are installed either side of the crack, the demec gauge (Figure 8.2) is temporarily attached to measure strain, which is converted to displacement. The equipment includes an invar reference bar to make minor temperature corrections for changes in ambient temperature.

The accuracy is +/- 0.001mm and the gauge length extends from 50 to 500mm. There are MSDOS software programmes to simplify analysing results.

The technique is relatively cheap and highly accurate. Before installing the plates, you would need to consider how to maintain the integrity of the spillway. Measurements cannot be automated. Therefore, this type of technique would be suited to short-medium term monitoring of cracks.

Figure 8.2: Demountable mechanical (demec) strain gauge (Source: Accolade Measurement, 2016)

8.4.3 Plastic Tell-Tale gauge

This technique monitors crack width at a specific location. The instrumentation (Figure 8.3) is permanently in place and measures 2 orthogonal movements. The accuracy is +/- 1.0mm and can typically measure movement up to 20mm and 10mm.

It is a cheap, rudimentary and quick to install but effective technique. Measurements cannot be automated and require direct, close access. Therefore, it is suited to easily accessible hard surfaces of a spillway, such as the retaining walls. Before installing it within the spillway, the impact on hydraulics would need investigating. It is suited to short-term monitoring of one particular visual warning sign such as movement of one portion of a retaining wall.

Figure 8.3: Example of a plastic Tell-Tale gauge (Source: Severn Trent, 2021)

8.4.4 Potentiometer

This technique monitors crack width at a specific location. The instrumentation is permanently installed (Figure 8.4). As the crack width changes, the connection cable/ rod moves. The electrical output is converted to displacement in millimetres. The accuracy is +/- 0.003mm and can measure crack widths up to 80mm. Reading frequency can be set at different intervals.

The technique is relatively cheap and simple but highly accurate. As instrumentation protrudes and is affected by water it is not suitable within the spillway. It would be suited to short-medium term monitoring of cracks as measurements are automated, and data can be accessed onsite or remotely.

Figure 8.4: Example of a cable style potentiometer with onboard logging (Source: Avongard Limited)

8.4.5 Thermal infra-red imagery

A thermal Infra-red sensor mounted to a drone can be used to monitor cracks and defects across an extensive area. There is a variety of instrumentation offering different levels of detail. Accuracy can vary from 10mm to 500mm depending on the number of ground control points – see section 8.5.2 for further details. Figure 8.5 shows the technique can produce highly detailed outputs over an extensive area.

Artificial Intelligence can be used to tag and detect cracks, although so far it has generated limited success. At this stage trained data technicians produce a better quality output using manual image review and crack tracing/ identification.

The technique is relatively sophisticated and offers remote data acquisition. In order to analyse and detect change it is necessary to have future drone surveys of the same location and same ground control points. The technique is suited to short or medium-term monitoring of spillways where there are several warning signs.

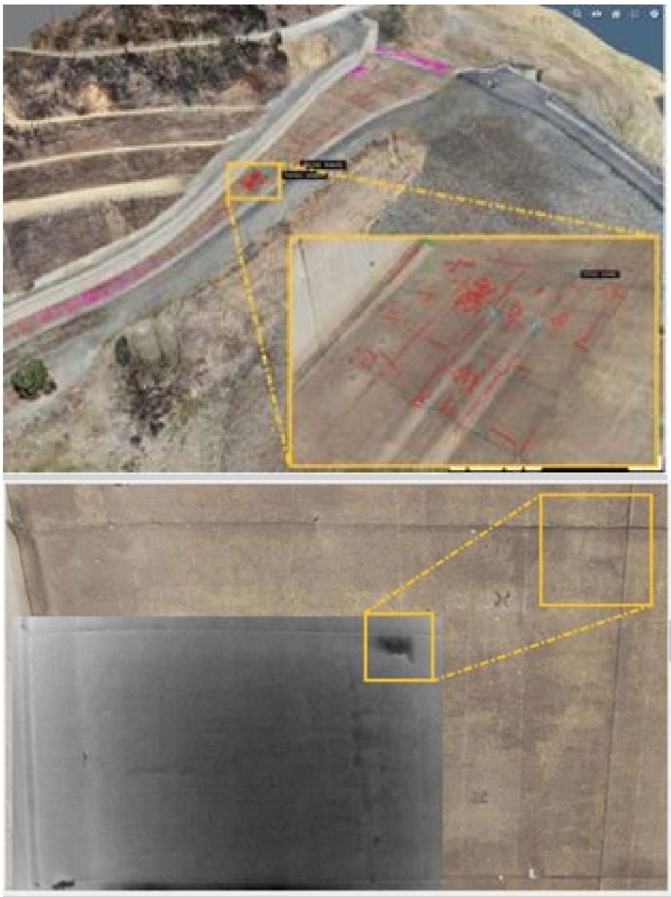

Figure 8.5: Examples of thermal infra-red imagery at a spillway (Source: Diospatial®)

8.4.6 Vibrating wire strain gauge

This technique monitors crack width at a specific location. The instrumentation (Figure 8.6) is permanently in place to measure strain[29], which is converted to displacement. The accuracy is +/- 0.06mm and the gauge length extends from 30 to 100mm. Reading frequency is less than one minute.

Measurements are automated, and data can be accessed remotely. As the instrumentation protrudes, it can be affected by water and give false readings, therefore it is not suitable within the spillway. It would be suited to short-long term monitoring of cracks along retaining walls.

Figure 8.6: Example of a vibrating wire strain gauge (Source: Accolade Measurement, 2016)

8.4.7 Vernier calliper

This technique can be used to monitor crack width at a specific location. The instrumentation measures displacement. A Vernier calliper is accurate to +/- 0.02mm and digital version (Figure 8.7) is accurate to +/- 0.01mm. Typically, the range is up to 150mm.

It is cheap, rudimentary and quick to install, but an effective technique. Measurements cannot be automated and require direct, close access. To enable repeated measurements from the same position, permanent reference points would be required. This can be achieved by installing purpose-made studs or, for a quick rudimentary solution, using normal screws and wall plugs. This type of technique would be suited to short-term monitoring of specific cracks that are easy to reach.

Figure 8.7: Example of a digital Vernier caliper measuring crack movement (Source: Avongard Limited)

8.5. Techniques to monitor movement

8.5.1 Acoustic emission

Acoustic emission has become an established approach to monitor the stability of soil slopes (Zaki and others, 2014) in other environments. For example, the Environment Agency installed the technique as part of an early warning system during the construction of a new flood defence at South Ferriby, Humber Estuary. Figure 8.8 provides an illustration of the instrumentation. The associated sensors are now available commercially[30].

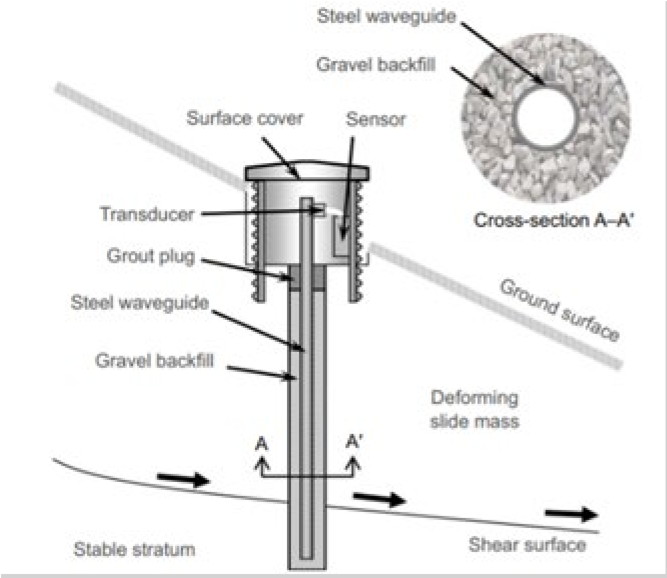

Figure 8.8: Schematic illustration of the instrumentation for acoustic emission monitoring (Smith and others, 2014)

A study in 1978 proved that actively deforming soil masses generate a high level of acoustic emissions (Koerner and others, 1981). Dixon and others (2003) showed, via 2 full-scale field trials, that acoustic emissions can provide early indication of slope instability in conjunction with relevant signal processing methods. UK field trials in 2014 proved that acoustic emissions (detected from an active waveguide) are directly proportional to the velocity of slope movement (Smith and others, 2014). The trials also showed that active waveguides can provide continuous information on slope displacements and displacement rates with high temporal resolution. Another trial has been performed at a rail cutting in the UK with the active waveguide subsurface instrumentation, unitary battery-operated acoustic emission sensor and warning communication system (Dixon and others, 2015). That study demonstrated that acoustic emission monitoring can again provide continuous information on displacement rates, with high temporal resolution. It also showed the ability to disseminate warnings by way of text messages.

The studies indicate that acoustic emissions have the potential to detect developing internal erosion in a reservoir embankment and provide real-time information. Since then, Loughborough University has conducted research on the detection of internal erosion in earth dams using acoustic emissions. The work demonstrates that progressive particle movement can be detected. Further research would be necessary to determine:

- how to install instruments without affecting the integrity of the embankment
- whether the instrumentation could detect progressive strain of a spillway

It could be suited to short and long-term monitoring before there are visual warning signs. It also can contribute to safety warning systems.

8.5.2 Photogrammetry via a drone

Drones are now a mature technology and they are common across most industries. An RGB depth sensor mounted to a drone can be used to monitor movement across an extensive area. There is a variety of instrumentation offering different levels of detail. One of the most common data processing techniques is photogrammetry.

Photogrammetry is the process of 3D triangulation and model generation from georeferenced imagery. This process enables the creation of 3D models, pointclouds, 2D maps, elevations and a 3D digital elevation model (DEM).

Figure 8.9 illustrates that the technique can produce highly detailed outputs over an extensive area.

Figure 8.9: Examples of 3D models produced from drone imagery (Source: The Scan Station, 2021)

As photogrammetry uses photographic data to generate the desired outputs, the quality and operation of the camera system can significantly impact these outputs. Images must be well focused, correctly exposed, and appropriately captured for good results. As all of this must be monitored by the pilot while controlling the flight, experience can greatly influence the quality of the outputs.

In order to ensure that the data is not just visually appealing but also geospatially correct and measurable, it is important that a survey is 'controlled'. Many modern drone systems have onboard RTK GPS systems (image of M300 RTK drone) that can accurately place the drone to within a few centimetres and act as onboard survey control. Although for many surveys this provides sufficient accuracy, it should be validated against ground control points (GCPs)[27]. The pattern (location) and number of GCPs defines the accuracy of the survey and any 3D models produced. To increase the reliability, special attention should be paid to the marker placement, in particular near the spillways, any balustrades and the hydrostatic level (Ridolfi and others, 2017).

When procuring a drone survey, a reservoir manager/undertaker should ask the supplier to explain how GCPs will be used to validate accuracy. Accuracy of the DEM can vary from 10mm to 500mm depending on the number of GCPs. It should be noted that the GCPs should be established to the current Ordinance Survey geoid, they should have proven quality control, and the overall accuracy will improve with more GCPs. Drone surveys can be processed alongside other 3D datasets, including terrestrial laser scanning for increased coverage and accuracy. Other insights on using remotely operated vehicles are shown in Table 3.1.

The technique is relatively sophisticated and offers remote data acquisition. Companies with a proven surveying track record should be used to maximise accuracy. Data acquisition is relatively quick; data obtained in one hour typically takes 2 to 5 days with a scanner. Data processing is typically completed within 2 days. In order to analyse and detect change, it is necessary to have future drone surveys of the same location and same ground control points.

The technique is suited to short or medium-term monitoring of spillways. This technique can be limited due to unsuitable weather such as high winds and rain. Care should also be used where there is dense vegetation such as tree canopies as this will affect the accuracy around that area.

8.5.3 Plastic displacement Tell-Tale gauge

This technique can be used to monitor movement at a specific location. The instrumentation (Figure 8.10) enables horizontal and vertical displacement measurements. The vertical displacement range is only 110mm. The horizontal range is -10mm to +50mm. The graduated ruler can be removed between readings. It is recommended that the same person reads the gauge where possible. It is a cheap, rudimentary and quick to install but

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[27] used to geo-reference the dense point cloud. Ground control points are accurately surveyed known points (either existing features such as a known point on an access/maintenance cover, or purposefully placed targets) that can be selected and checked against during the data processing stages.

effective technique. Measurements cannot be automated and require direct, close access. Therefore, it is suited to easily accessible hard surfaces of a spillway, such as the top of retaining walls. Before installing it within the spillway, the impact on hydraulics would need investigating.

It is suited to short-term monitoring of one particular visual warning sign such as movement of one portion of a retaining wall.

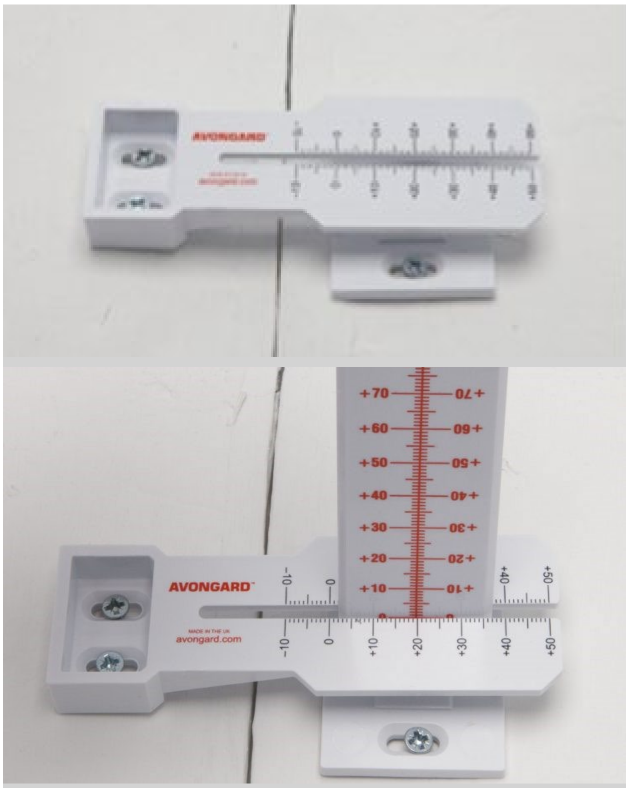

Figure 8.10: Illustrations of a plastic displacement Tell-Tale gauge (Source: Avongard Limited)

8.5.4 Robotic total station

This technique can be used to monitor subtle movement across a specific area. The instrumentation (Figure 8.11) measures horizontal and vertical positions. The equipment is lightweight and portable. Sophisticated technology means that measurements are accurate, and information is collected quickly. A typical total station can measure distances up to 1,500m with an accuracy of about 1.5mm. Once set up, it can be operated from a distance and multiple surveys are possible from one location. Survey data can be easily downloaded for interpretation and to create a digital elevation model.

Automated total stations can be installed for remote and continuous measurements that would help detect movement. This requires stable and secure installation. A suitable raised position, as shown in Figure 8.11, could be difficult to arrange next to a spillway.

Therefore, this type of technique would be suited to short-term monitoring of a few visual warning signs, such as movement and misalignment of slabs or retaining walls.

Figure 8.11: Example of a robotic total station (Source: Leica Geosystems AG - Part of Hexagon)

8.5.5 Satellite imagery

Satellite imagery from earth observation satellites can be used to monitor movement across an extensive area. The synthetic-aperture radar (SAR) has evolved to give +/- 2mm accuracy compared to 15 to 30mm using drones. SAR is gathered by Sentinel 1, which was launched in 2016 and automatically collects data every 6 days in the UK. SAR is not inhibited by light or weather.

Using satellite imagery is a sophisticated technique that does not require direct access to the dam. It is suited to long-term monitoring of the whole spillway and surrounding embankment. Data from satellite monitoring system requires expert interpretation.

There are currently 2 products in the UK market: DAMSAT[28] and iDMS[29]. Both of these, monitor and analyse other dam characteristics (for example, ground motion, vegetation and moisture) to indicate if there is a deviation from the normal basal rhythm. Both systems are being trialled at a number of dams: Bristol Water[30] is an early adopter of DAMSAT; the Canal & River Trust[31] is an early adopter of iDMS.

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[28] Owned by HR Wallingford.

[29] Intelligent Dam Monitoring System, owned by Binnies.

[30] https://utilityweek.co.uk/improving-safety-from-the-skies-how-damsat-is-protecting-bristols-dams/.

[31] https://construction-update.co.uk/2021/04/21/canal-river-trust-adopts-binnies-and-rezatecs-satellite-based-intelligent-dam-monitoring-system-idms/.

For DAMSAT, satellite images are refreshed every 10 days from open source 10m x 10m pixels and it can take approximately up to 3 weeks to process imagery. Figure 8.12 provides an illustration of a display from DAMSAT.

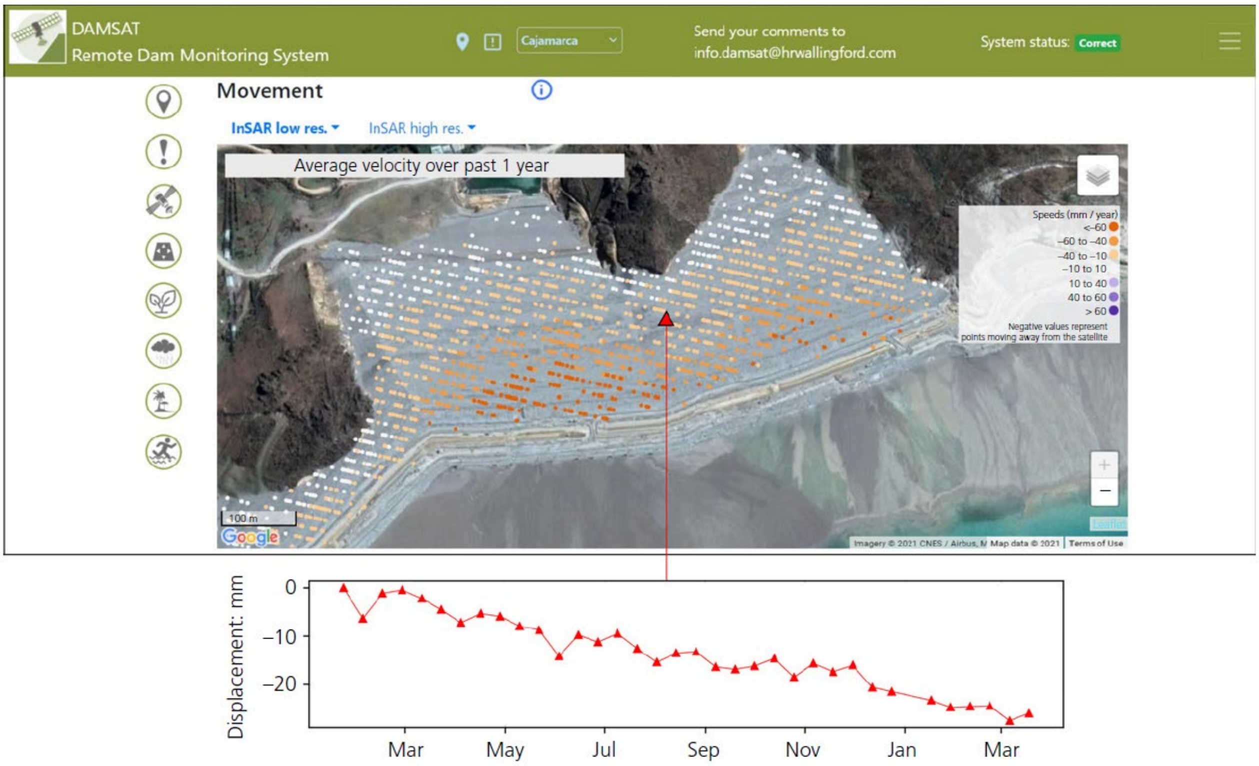


Figure 8.12: An illustration of a display from DAMSAT (Source: Goff and others, 2021)

For iDMS, data processing takes about 3 weeks and the resolution is 9m or 30m hexagons. Satellite imagery for iDMS is available from 2016, allowing retrospective and current analysis to build a unique picture over time. **Figure 8.13** provides an illustration of a display from iDMS.

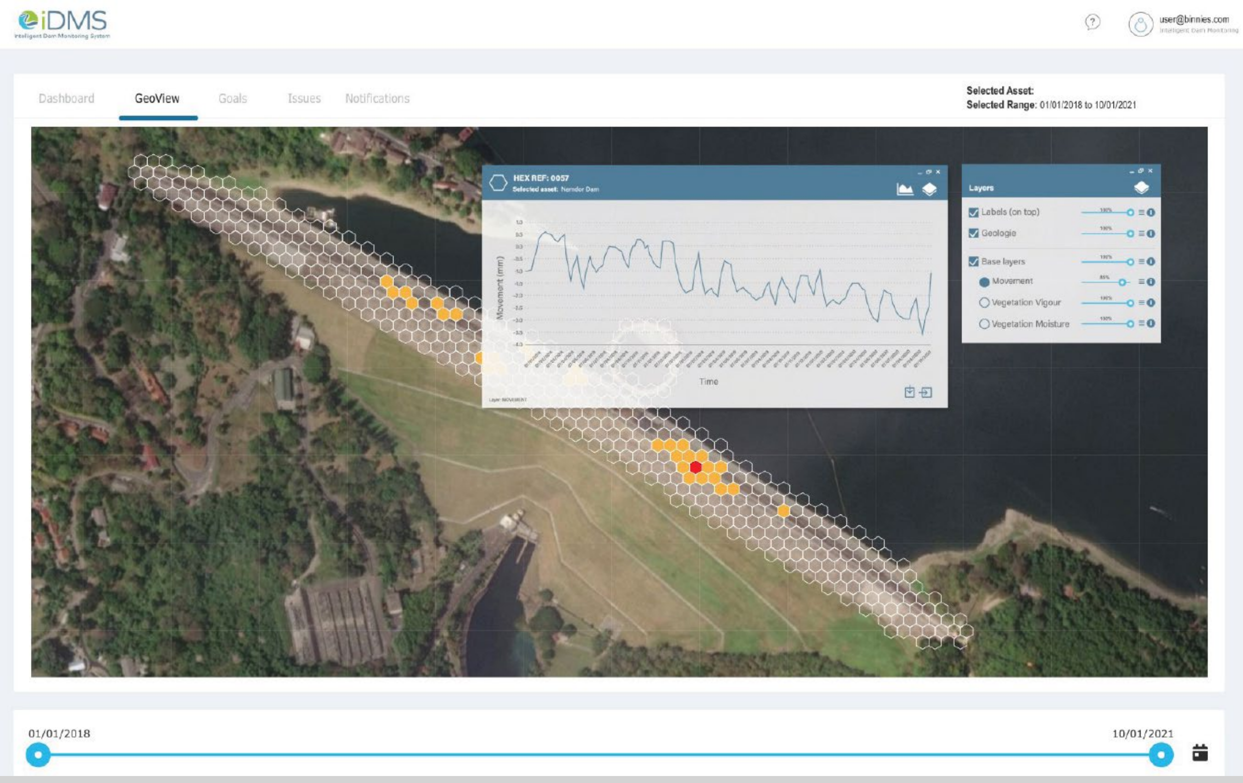


Figure 8.13: An illustration of a display from iDMS (Source: Binnies, 2021)

8.6. Techniques to monitor seepage

8.6.1 Ground penetrating radar

As explained in Chapter 7, this technique can detect signs of underground voids or seepage paths but not water flow. When the technique is repeated, it is possible to monitor changes in size and location of voids. Illustrations of the instrumentation are shown in Appendix E. Depth accuracy is typically 15 to 20% without calibration and 10% or better with calibration (using cores or drill holes).

It is a sophisticated technique and specialists are required to evaluate the information. When the technique is repeated in the same area at specific intervals, it will indicate changes to the voids.

It would be suited to short to medium term monitoring as it can give full continuous coverage of spillway but requires direct, close access to the spillway.

8.6.2 GroundSat analysis

As explained in section 7.6, this technique measures relative soil moisture beneath the surface, including concrete. The technique relies on satellite imagery and so can cover the whole spillway and dam. Horizontal resolution is 3m to 6m.

Data acquisition is remote and takes 2 to 3 weeks, plus a further 2 weeks for analysis. Given the wide coverage, it would be suited to medium to long-term monitoring.

8.6.3 Measurement container and stopwatch

This technique can be used to monitor flow from some seepage locations. For large volumes a bucket can be used. Where water is spouting out from a hole, crack or an installed small collection pipe, a smaller jug as shown in Figure 8.14 can be used. It is advised to use a constant (either in volume or time) and plot the data against other known information, such as reservoir level or rainfall data.

This technique requires minimum equipment but can yield important information. Additionally, flow can be collected in sealable containers and allowed to settle, thereby giving an indication of the fines in the seepage water.

It is a cheap, rudimentary, quick to use and effective technique. It is also a practical technique as equipment can be easily stored in a vehicle or on site. It requires direct access unless the water can be piped to a collection point. Care should be taken that any collection system does not interfere with the flow of the spillway. This technique would be suited to short-term, one-off monitoring.

Figure 8.14: Example of a measurement container (Source: Richard Terrell, 2021)

8.6.4 Piezometer

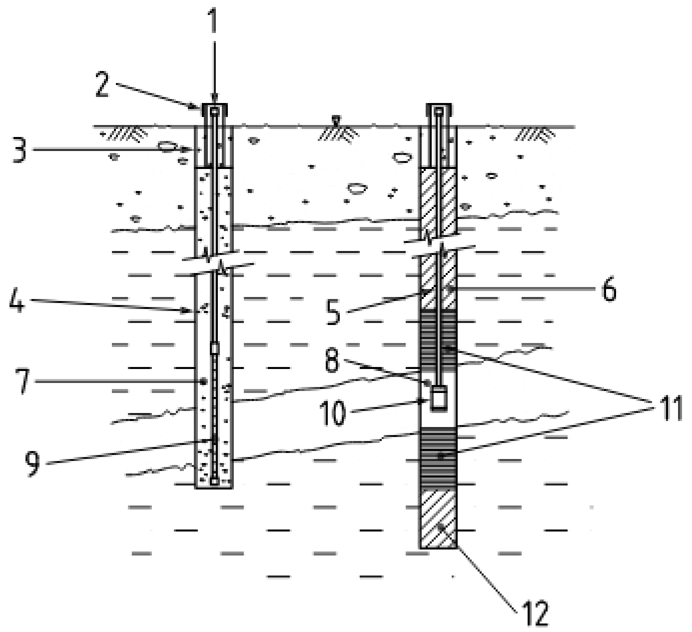
This technique can be used to monitor the phreatic surface within the dam shoulders. Most often the piezometers are installed by drilling (for example using a borehole rig) and contain a deep and shallow instrument, as shown in Figure 8.15. The piezometer can be read manually using a dip meter or by using a pressure sensor and data logger to gain a more definitive data set. Piezometers should be levelled into the same datum as the reservoir and results plotted to give corresponding information to reservoir water levels.

Piezometers only work around their zone of influence which depends on the soil makeup within the embankment. Therefore they may not give an accurate indication of the true phreatic surface within the embankment (ICOLD Bulletin 164). Piezometers are unlikely to detect concentrated leak erosion.

Retrofitted installation of new piezometers can be expensive and depending on location, they can prove difficult to install, such as on a steep slope. Hand driven piezometers can be installed quicker but they are not suitable for all sites as depth limitations vary with soil conditions and drive methods used.

The technique is suited to medium-long term monitoring.

Examples of observation well and standpipe piezometer construction



Key

1	Ventilated plastic cap	7	Gravel or sand backfill
2	Protective metal cover	8	Sand filter
3	Concrete plug	9	Perforated plastic pipe at base
4	19 mm – 50 mm ID plastic pipe	10	Low air entry porous ceramic or plastic filter
5	12 mm – 19 mm ID plastic pipe	11	Compacted and hydrated bentonite seals
6	Grout seal	12	Compacted backfill

NOTE Adapted from Clayton et al., 1995 [22].

Figure 8.15: Example of a piezometer (Source: BS 5930)

8.6.5 V-notch weir

V-notch weirs can be installed at the end of a collection system to measure the flow, and can be all sizes. Collection systems can be installed to channel flow from the point of issue to a safer or more convenient location to measure. Care should be taken if a collection system is installed in the spillway that is does not cause turbulence or cross waves and that it is durable enough to withstand the water force within the spillway and not become damaged.

The V-notches should follow the standard of an internal angle of 45^{o} or 90^{o} and be manufactured to BS3860. The weirs can be installed in either purpose-built brick or concrete chambers or can be prefabricated out of stainless steel or plastic. It is important that the chambers do no leak and have sufficient space to allow the outlet to freely discharge. A method of measurement, be it a steel ruler or gauge board needs to be implemented. More sophisticated measurement methods using pressure sensors or ultrasonics can be used linked to data loggers and telemetry. Calibration should be carried out periodically. The practice of putting the ruler in the base of the V-notch to measure should be discouraged as this can provide a false reading.

The V-notch chamber can also act as a settlement chamber to collect any particles that are being carried by leakage water for analysis.

This technique can be used for long-term monitoring of the leakage rate and should be linked to other readings such as reservoir level and rainfall. A typical installation is shown in (Figure 8.16).

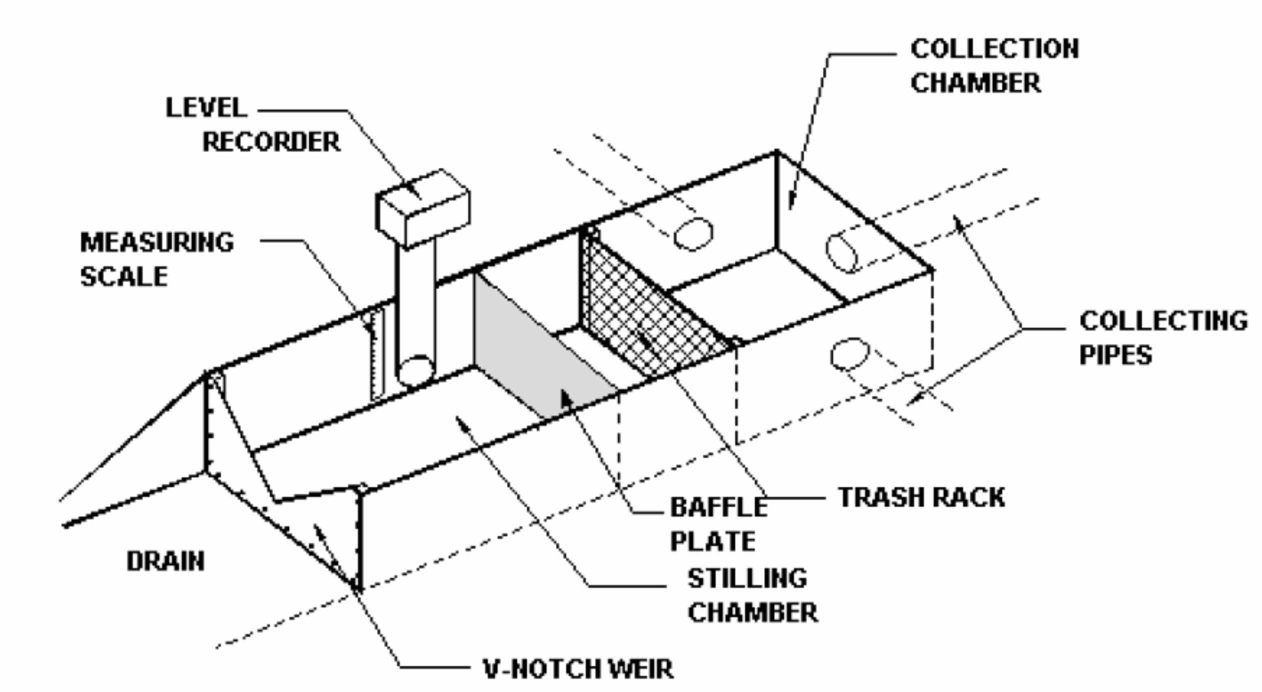


Figure 8.16 Example of an arrangement for a V- notch weir (Source: Defra, 2007)

8.6.6 Water sampling

This technique can be used to monitor the chemical makeup of the leakage water. Samples are taken within the reservoir basin and at the point of leakage. These samples can then be sent to a laboratory for analysis of the chemical makeup and mineral content of the water. The analysis can help determine if the leakage water is from the reservoir or from another source such as rainfall or ground water.

Samples need to be taken manually and using clean purpose-made sample jars and bottles to prevent any contamination of the results and at the right quantity. Specialist laboratories will need to be used to undertake the test, and the results can often take a few days to obtain.

8.7. Further reading

The following publications offer more details on monitoring:

- FERC, 2020. 'Chapter 9 Instrumentation and Monitoring' – provides detailed information on philosophy of instrumentation and monitoring, types of instrumentation, minimum recommendations for existing and proposed dams, design of systems, monitoring schedules, data processing, evaluation of data and automation. Basic requirements on successful automated data acquisition is based on a 1993 USCOLD publication.
- FERC, 2020. 'Chapter 14 Dam safety performance monitoring programme' – Section 14.4 provides detailed information on surveillance and monitoring plans. It gives fundamental principles and methods in the evaluation of the performance of a dam. Appendix K provides questions to assist the evaluation of instrumentation.
- CIRIA C743, 2015. 'Dams and reservoir conduits. Inspection, monitoring, maintenance and repair' – Chapter 6 covers monitoring techniques, setting up a monitoring programme, data acquisition and trend analysis.
- DEFRA, 2007. 'Guidance Note on Real time monitoring of dams for early detection of internal erosion' – Chapter 4 gives details regarding physical installation of V-notch weirs.

Glossary of terms and abbreviations

ASTM: American Society for Testing Materials - an association that publishes standards and requirements for materials used in the construction industry.

Anchors: A system of stressed steel rod/tendons/bars within or attached to a structure to provide structural support.

As-built drawings: Plans or drawings portraying the actual dimensions and conditions of a structure as it was built. Field conditions and material availability during construction may change from the original design drawings.

ASDSO: Association of State Dam Safety Officials.

Berm: A horizontal step or bench in the sloping profile of an embankment.

BRE: Building Research Establishment.

Catchment: The area of land draining into a reservoir.

Channel: The part of a natural or artificial watercourse which periodically or continuously contains moving water, or which forms a connecting link between 2 bodies of water. It has a defined bed and banks that serve to confine the water.

Chute: An open channel (usually paved) which carries water away from the spillway inlet structure (sometimes referred to as headworks) and transmits it downstream. This is also known as the conveyance structure/channel.

CIRIA: Construction Industry Research and Information Association.

Conduit: A closed channel to convey water through, around, or under a dam.

Conveyance structure: A structure to safely convey the water from the inlet structure and discharge it downstream of the dam. It could take the form of an open channel, sometimes referred to as a 'chute', or a conduit (pipe, tunnel or culvert) where flow may run under free surface or under pressure.

Core: The central part of an earth embankment dam that provides water tightness.

Corrosion: The chemical attack on a metal by its environment. Corrosion is a reaction in which metal is oxidised.

Crack/joint movement: It is defined as horizontal or vertical movement of one part of a structure relative to another part of a structure.

Crest: The top of a dam, spillway or embankment.

CRT: Canal & River Trust.

Cut-off: An impervious construction or material which reduces seepage or prevents it from passing through foundation material. It is often used to provide a watertight seal at the base of the core of the dam or between the crest of a spillway and the core.

Defra: Department for Environment, Food and Rural Affairs.

Dewatering: The removal of water from an area.

Drainage: The removal of excess surface water or groundwater from land by ditches or subsurface drains.

Drains: (1) Relief wells – A vertical well or borehole, usually downstream of impervious cores, grout curtains, or cut-offs, designed to collect and direct seepage through or under a dam to reduce uplift pressure under or within a dam. A line of such wells forms a drainage curtain. (2) A buried slotted or perforated pipe or another conduit (subsurface drain) or a ditch (open drain) for carrying off surplus groundwater or surface water.

Draw down: The controlled lowering of the water surface level in a reservoir.

Dowel bars: Steel bars that join one slab to the adjacent one, or another part of the structure. They help to prevent movement of one slab from the next.

Energy dissipation structure: A structure that dispels residual kinetic energy of water exiting from the conveyance structure in order to prevent excessive erosion downstream. Such erosion could have the potential to undermine the energy dissipator, the entire spillway structure and initiate head-cutting of the embankment or cause unacceptable erosion of the downstream receiving watercourse or natural ground.

Failure: The uncontrolled release of water from a dam.

Failure mechanism: It is a physically plausible process for a structure to collapse or disintegrate, which can lead to an uncontrolled release of impounded water.

FEMA: Federal Emergency Management Agency.

FERC: Federal Energy Regulatory Commission.

Grout: A fluidised material that is injected into soil, rock, concrete, or other construction material to seal openings and to lower the permeability and/or provide additional structural strength. There are 4 major types of grouting materials: chemical, cement, clay and bitumen.

Hydrostatic pressure: The pressure exerted by water at rest.

Headworks: see 'Inlet structure'.

ICOLD: International Commission on Large Dams.

Impounding: Reservoirs that receive their inflow from a river or watercourse.

Inlet structure: (1) In most cases, this is a freely discharging weir which controls the reservoir outflow. The weir could take different cross-sectional shapes, including ogee, trapezoidal, rectangular, triangular (crump weir or other) and sharp-crested. Different configurations in plan also exist, the simplest and most common being the straight weir. Circular weirs are typically provided as the inlet of shaft (bellmouth) spillways. Non-linear in plan weirs, including labyrinth weirs and their 'piano-key' variation, provide an increased weir length where limited space is available. An inlet structure is sometimes known as the 'headworks'. (2) In some applications, the control of the reservoir level and reservoir outflow is provided by permanent gated structures, temporary collapsible gates or sacrificial embankments referred to as 'fuse-plugs'.

Inspecting engineer: A qualified engineer responsible for inspecting reservoirs under the provisions of the Reservoirs Act.

Instrumentation: An arrangement of devices installed into or near dams that enable measurements that can be used to evaluate the structural behaviour and performance parameters of the structure.

Internal erosion: A general term used to describe all the various erosional processes where water moves internally through or adjacent to the soil zones of embankment dams and foundation, except for the specific process referred to as backward erosion piping. The term internal erosion is used in place of a variety of terms that have been used to describe various erosional processes, such as scour, suffusion, concentrated leak piping, and others.

Internal movement: Defined as horizontal or vertical movement within the structure.

Intrusive: Where a structure is cut open or excavated to see the subsurface, resulting in partial, temporary damage.

Lateral: Across the direction of flow. See also 'Transverse'.

Leakage: Uncontrolled loss of water by flow through a hole or crack.

Non-destructive: Sometimes known as 'reconnaissance investigation's, 'non-destructive evaluations' or 'non-invasive' where a structure's integrity remains intact.

Outlet (outlet works): An opening through which water can be freely discharged from a reservoir, or the point of water disposal from a stream, river, lake, tidewater, or artificial. Used to lower the top water level in reservoirs. See also 'Energy dissipation structure'.

Outlet channel (Discharge channel): A waterway constructed or altered primarily to carry water from man-made structures, such as dam spillways, smaller channels and diversions.

Overflow: A structure built to allow a body of water to overflow.

Petrographic: Analysis to study the mineralogical and chemical composition of materials.

Phreatic surface: The free surface of water seeping at atmospheric pressure through soil or rock.

Piezometer: An instrument for measuring the pore water pressure within soil, rock, or concrete.

Piping: The progressive development of internal erosion by seepage.

Pressure relief pipes: Pipes used to relieve uplift or pore water pressure in a dam foundation or in the dam structure.

Relief well: See 'Drains'.

Reservoirs Act: The 1975 Act forms the basis for regulation of reservoirs in England. It was amended by the Floods and Water Management Act 2010.

Reservoir manager: Any person who owns, manages or operates a reservoir or any part of it.

Reservoir undertaker: The organisation or individual legally responsible for the operation of a dam This is sometimes known as an 'operator' or 'owner'.

Risk: The combination of probability and consequence. Note that the term is often misused, either as a substitute for probability or a substitute for consequence.

ROV: Remotely operated vehicle. This is typically terrestrial or underwater.

Sill: (1) A submerged structure across a river to control the water level upstream. (2) The crest of a weir or spillway. (c) A horizontal gate seating, made of wood, stone, concrete or metal at the invert of any opening or gap in a structure, hence the expressions 'gate sill' and 'stoplog sill'.

Scour: Erosion occurring due to the flow of a fluid over an erodible material.

Seepage: The movement of water through a dam, its foundation, or its abutments and emerging on the downstream slope.

SEPA: Scottish Environment Protection Agency.

Settlement: The vertical downward movement of a structure or its foundation.

Shear: The sliding of one surface of a material over another.

Slip: Instability failure of soil due to insufficient shear strength.

Slope: (1) The side of a hill or mountain. (1) The inclined face of a cutting or canal or embankment. (3) Inclination from the horizontal. The term is used for any inclination and is expressed as a percentage when the slope is gentle, in which case the term gradient is also used. In the United States, it is measured as the ratio of the number of units of horizontal distance to the number of corresponding units of vertical distance.

Spalling: Breaking (or erosion) of small fragments from the surface of concrete masonry or stone under the action of weather or abrasive forces.

Shaft spillway: A vertical or inclined shaft into which flood water spills and then is conducted through, under or around a dam by means of a conduit or tunnel. If the upper part of the shaft is splayed out and terminates in a circular horizontal weir, it is termed a 'bellmouth' or 'Morning Glory' spillway.

Spillway: A structure or structures that safely convey(s) excess flows during storm events through, around or over the dam, while maintaining appropriate flood freeboard.

Stagnation pressure: The pressure created when a flowing fluid is stopped by collision with a solid surface.

Stilling basin: A basin constructed to dissipate the energy of fast-flowing water, for example, from a spillway or bottom outlet, and to protect the bed of the downstream watercourse from erosion.

Suffusion: A type of internal erosion where fines are transported by seepage flow from one location to another.

Supervising engineer: A qualified engineer appointed to supervise a reservoir under the provisions of the Reservoirs Act.

Surface movement: Defined as horizontal or vertical movement of a point on the surface of a structure relative to a fixed point off of the structure.

Sweep-out: Excessive scouring of the downstream riverbed and basin structure.

Tailwater: The water surface elevation at the downstream side of a hydraulic structure such as a culvert, bridge, weir or dam.

Transverse: Perpendicular to the direction of flow. See also 'Lateral'.

Toe drain: A system of pipe and/or pervious material along the downstream toe of a dam used to collect seepage from the foundation and embankment and convey it to a free outlet.

Toe of dam: The lowermost portion of the dam embankment where it intersects the ground surface. Also, referred to as the 'downstream toe'. For an embankment dam, the junction of the upstream slope with the ground surface is called the 'heel' or the 'upstream toe'.

Toe of slope: The base or bottom of a slope at the point where the ground surface abruptly changes to a significantly flatter grade.

TWL: Top water level. For a reservoir, this is usually taken as the level of the primary spillway weir crest. The level in the reservoir will exceed TWL when the spillway(s) operate.

Turbidity: (1) Cloudiness of a liquid, caused by suspended solids. (2) A measure of the suspended solids in a liquid.

UAV: Unoccupied aerial vehicle.

Underdrain: A small diameter perforated pipe or a filtered drainage layer/trench under a spillway, embankment or other structure that allows any seepage water to drain away. It helps control uplift pressure.

Uplift: The hydrostatic force of water exerted on or underneath a structure, tending to cause a displacement of the structure.

USACE: United States Army Corps of Engineers.

USBR: United States Bureau of Reclamation.

USSD: United States Society on Dams.

V-notch: A vee shaped notch cut into a plate and set in the flow. It enables the rate of flow to be deduced from the water level.

Water-bar: Flexible material cast into adjacent slabs of concrete to prevent water penetrating through the joint between the slabs. Sometimes referred to as a ‘water-stop’.

Weir: The top edge of an overflow or spillway over which the water flows. See also ‘Sill’ and ‘Inlet structure’.

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Appendix A – Supplementing Chapter 2

Appendix A1. Context for the inspecting engineer's principles

Recommendation 2 by Professor David Balmforth (Defra, 2019) provides the starting point for the principles contained in section 2.3. It sets the expectations for inspecting panel engineers – spillways should be inspected closely, that is, within touching distance by direct access, wherever practicable and safe to do so. The reasons for this are:

A. legal obligation[32] to assess and report on the adequacy and condition of spillways as part of the statutory inspection
B. close examination, within touching distance by direct access, greatly enhances the likelihood of identifying all significant defects, and enables potential defects to be probed

To consider nuances and any exceptions, it is important to appreciate the context and purpose. This stems from the objectives and outputs of a statutory inspection in relation to carrying out a spillway examination:

- objectives – to determine the spillway condition and to form an opinion as to whether it can bear the next flood and the safety check flood without threatening the integrity of the dam
- outputs – are recorded in an inspection report. When the inspection cannot provide a conclusion, further studies and investigations are recommended. They often become measures in the interest of safety

To achieve the objectives, an inspecting engineer appraises information relating to the spillway. They will consider a range of aspects, such as design, construction, flood studies, historical repairs, past inspection reports and how it behaves when operating. This reveals that up-close examination by direct access is essential, but not the only source of information required to complete the task. Therefore, this guide contains principles and insights that support the preparation for an inspection and appraisal of information in section 3.3.

The safety of the inspecting engineer, and any supporting personnel, is of paramount importance when examining the spillway. While the reservoir manager/undertaker should take all reasonable steps to create safe and direct access (section 2.2), not all inspecting

[32] Schedule 5 of Statutory Instrument 2013 No. 1677 for England, Schedule 5 of Welsh Statutory Instruments 2016 No. 80 (W.37) Flood Risk Management, Wales, Section 47 in the Reservoirs (Scotland) Act 2011, and may be referred to as Section 35 in Northern Ireland when the relevant section of the Reservoirs Act (NI) 2015 is commenced.

engineers will be comfortable with the available access system. Therefore, there should be an allowance for an inspecting engineer to choose an equivalent method of observation that allows them to achieve the same level of certainty regarding the condition of the spillway to meet the above objectives.

If the spillway is not dry or accessible on the day of the visit due to unforeseen situations, inspecting engineers should have some freedom to determine a suitable outcome based on the safety of themselves or others. Section 2.3 outlines principles to help their decision-making.

It is important to recognise that although a dry spillway provides the opportunity for close inspection by direct access, it might not exhibit visual warning signs that occur when it is passing water. This raises questions whether, in order to form an opinion on the adequacy of the spillway, an inspecting engineer must make several visits to observe the spillway in person or can rely on information provided by the reservoir manager/undertaker. This matter is clarified in section 2.3.

Appendix A2. Context for the Supervising Engineer's principles

Recommendation 2 by Professor David Balmforth (Defra, 2019) provides the starting point for the principles contained in section 2.4. It sets the expectations for supervising panel engineers – spillways should be examined closely, that is, within touching distance by direct access, wherever practicable and safe to do so.

To consider this further, it is useful to appreciate their role, the range of existing spillways, the advances in technology, reservoir operation and safety. According to the current UK reservoir legislation, pertinent roles relating to spillway examination are:

- a supervising engineer notifies the reservoir manager/undertaker about any safety issues related to the reservoir
- the scope of what a supervising engineer watches and oversees is mostly specified in safety reports, preliminary and final certificates as well as inspection reports
- a supervising engineer notifies the reservoir manager/undertaker if certain activities/ matters[33] are not complied with

The frequency of visits by a supervising engineer is often included in the scope of what they are to watch (second bullet above). The second edition of the ICE Guide to the Reservoirs Act 1975 remarks that the frequency of these visits is commonly once or twice a year. In addition, to observe changes at the reservoir and advise on safety, a supervising

[33] Each national legislation explains these as 'provisions' in certain sections of acts. Broadly they relate to keeping a record of change over time, construction or enlargement of reservoirs and re-use of abandoned reservoirs.

engineer can choose to change the frequency (ICE, 2014). So, the principles for examining a spillway by a supervising engineer should have a similar degree of freedom to increase the frequency as they see fit.

The next 2 factors indicate that there could be situations where equivalent examination methods other than direct access would be appropriate:

- Range of concrete spillways – They vary in the UK in shape, age, type, scale and form. Some are as little as 1.5m wide, while others span tens of metres. Gradients can be walkable shallow slopes without safety equipment or steep slopes requiring specialist access equipment. The length of the spillway might be a short 20m distance or travel extensively over 100m. Therefore, some spillways could be adequately examined by walking alongside them rather than directly within them.
- Advances in technology – remotely operated vehicles (ROVs) and unoccupied aerial vehicles (UAVs) with sophisticated cameras can enable anyone to safely examine the entirety of a spillway, whether via real-time or recorded footage.

Existing reservoir operation influences the interpretation of Recommendation 2. A spillway that operates continuously might not be examined closely and directly often compared to one that has never operated. This raises 2 questions:

1. If a supervising engineer continuously uses an equivalent method of examination/observation, should there be a trigger or threshold to perform a close, physical examination by direct access?
2. For a supervising engineer to fulfil their role, they ought to observe the spillway in different conditions, but should this be in person or via a recording?

These matters are not straightforward. One route could be to create a similar principle sometimes used in asset inspection, whereby the trigger is a specific period of time that an element has not been visited. However, this approach does not take into account local circumstances. The person who can appreciate local factors and consider complex issues is the inspecting engineer, particularly the one who performed the last statutory inspection. It is expected that these matters will be covered by future reports on statutory inspections or directions by construction engineers. In the interim, an inspecting engineer should be consulted to reach a decision. In a similar fashion, if the last inspection report does not explicitly mention the spillway, the supervising engineer should speak with the last inspecting engineer to agree on scope to monitor.

Lastly, the safety of the supervising engineer is of paramount importance. Recommendation 3 is clear that the reservoir manager/undertaker should take all reasonable steps to create safe and direct access for routine examinations. However, not all supervising engineers will be comfortable with the chosen access system. Therefore, in a similar approach for inspecting engineers, there should be an allowance for a supervising engineer to choose an equivalent method of examination. Given that examination of the spillway is more frequent than that by an inspecting engineer, it is reasonable that equivalent methods of examination by means other than direct access are more likely to be used by the supervising engineer.

Appendix B – Supplementing Chapter 3

Appendix B1. Prompts to help evaluate information and spot potential issues

The principles and prompts should be viewed as stimuli rather than as an exhaustive checklist.

Table B1: **Principles and prompts to help evaluate information and spot potential issues**

Universal principles	Prompts/ explanations
1. Think like a detective	• This is an overarching principle and will help uncover potential vulnerabilities when using the other principles
2. Identify the spillway design/assumptions	• Consider how the hydrologic design was developed and whether any parameters have changed which could affect the reservoir safety or performance • Is the spillway capable of passing projected flood flows based on the current hydrological assessment method? • Was the spillway designed to operate frequently? • Review the geological and geotechnical studies, noting the earth material erodibility • Do any geological faults or shear zones exist? • How is surface water and groundwater managed locally?
3. Consider if there are any features that are not typical of other spillways	• Compare the original design and as-built drawings against current standards, for example, against the Reservoir Spillways Design Guide (Environment Agency, 2022) • Are all 4 measures to prevent undermining present, that is, waterstops, cutoffs, adequate drain filtering and joint supports (Young and others, 2010)? If one is missing there is a higher chance that undermining could occur • Note any obsolete component configuration, equipment, or other features. For example: - older methods of shaping inlets for gates - poor hydraulic shape of spillways and water passages, with abrupt bends that could cause flow separation, uplift, and cavitation - obsolete types of spillway gates, including counterweighted gates, bear trap gates, and roller gates - needle beams on spillways as they are hard to control and weather severely • If no design/as-built information exists or it is limited, use detective skills to deduce possible as-built features. Two approaches below can assist. 1. Consider the date of the design, the time of relevant USBR publications and if the engineers would have known about them. Young and others (2010) discovered that while 1960 to 1980's editions of USBR's Design of Small Dams addressed spillway undermining, some constructed spillways from the period did not include any or all of the recommended prevention measures 2. Compare the period of construction to historic concrete spillway design developments: - use of reinforced concrete became more common (1905 to 1910)

Universal principles	Prompts/ explanations
3. Consider if there are any features that are not typical of other spillways (cont.)	- use of basic principles for producing modern concrete materials (1929) - air entraining agents were introduced to improve concrete's resistance to freeze/thaw damage (1930) - low water to concrete ratios and higher compressive strength became standard (after 1930) - internal vibration of concrete was used (1933) - improved construction joint clean-up was being used (1934) - Portland Cement Laboratories perfect air-entrained concrete (1940s) - alkali-silica reaction reducing practices were implemented (late 1940s) - United States Bureau of Reclamation (USBR) specifications required entrained air (1945) - reinforcement of earlier spillways often consisted of a single layer of reinforcement near the expose surface - USBR published 'Design of small dams' (1960) - the effectiveness of aeration to mitigate cavitation was demonstrated at Grand Cooulee Outlet Works (1961) - the first installation of a spillway aerator by the USBR at Yellow Dam Spillway (1967) - use of water-stops/water-bars became common (after 1960s and 1970s) - sulphate attack was virtually eliminated (1967) - USBR update 'Design of small dams' (1973) - USBR identified potential for stagnation pressures to develop at joints that are offset into the spillway flow and started to implement defensive measures (1976) - superplasticizers were introduced as admixtures (1980s) - concrete surface tolerance (requirements for cavitation indices) and finishes were separated in USBR designs (1987) - internal sulphate attack was identified in precast concrete and large volume concrete pours (1987) - USBR published Engineering Monograph No.42, 'Cavitation on Chutes and Spillways' (1990)
4. Look at how the spillway was constructed	• Was the spillway constructed as designed? • Have there been design revisions for any unusual or unanticipated site conditions? • Note any obsolete construction methods. Examples include: - conduit interiors not coated or lined - pipe joints not adequately sealed - no moisture control procedures for curing concrete - lack of controlled compaction along a conduit - copper water-stops/water-bars, which weaken over time and lack flexibility - concrete mixes not designed to resist local soil and water chemistry • Consider construction records and any issues with lining materials, concrete mix and the foundation (for example, differential settlement). Helpful questions include: • Are there any construction photographs showing the foundation preparation, anchors or lining reinforcement? • Has there been inadequate inspection during construction? Special attention should be given to items that, according to records, were not subject to inspection • Any evidence of prior wall/slab movement? Inadequate relief of water pressure behind walls or under slabs may be occurring, as well as settlement

Universal principles	Prompts/ explanations
5. Consider the evolution life of the spillway condition	• Start with the original design condition and associated drawings • Consider how the condition degrades over time or through internal/external processes, which degrades the structural and/or hydraulic performance • Is the local water quality harmful to concrete? (USACE, 1995) • Is there danger of spillway discharge undercutting components of the spillway? • How important is the evolution in terms of reservoir safety? • Has there been any base spreading? Unless the dam is founded on rock, joint separation at channel joints from base spreading may have occurred • What materials are nearing the end of life expectancy? • Have there been repairs and modifications? • Consider the effects of historic spill events • List out possible clues and signpost how to evaluate them

Appendix B2. A list of general considerations that would increase the spillway vulnerability and may lead to potential failure modes developing (adapted from Table 1 in Firoozfar and others, 2018)

The list should be viewed as stimuli rather than as an exhaustive checklist.

- Capacity deficiencies:
  - inadequate hydraulic capacity of the spillway
  - change in understanding of hydrology
  - change in understanding of larger spillway flood capacity requirements
  - blockage
  - inability to operate the gate system
  - modifications
- Geotechnical deficiencies:
  - landslide/rock fall into the spillway components
  - undermining of foundation due to leakage erosion/piping
  - rockslide/landslide and foundation failure
  - seismic consideration, for example, existence of faults
  - change in understanding of seismicity
- Hydraulic deficiencies:
  - cavitation
  - hydraulic stagnation pressure
  - spillway channel overtopping due to air bulking or wave action
  - outlet control (stilling basin) overtopping due to air bulking or wave action
- Structural deficiencies:

    - surface deterioration
    - structural gate members' inadequacy, deterioration/corrosion
    - slab failure due to deformation, settlement, and excessive net uplift pressures
    - structural failure during seismic event
  - Erosion and energy dissipation deficiencies:
    - spillway erosion
    - inadequate energy dissipation and downstream channel erosion and/or head-cutting
    - dam structure undercutting and/or undermining
  - Operational deficiencies:
    - control system deterioration, malfunction and failure (for controlled crest spillways)
    - underdrain system inadequacy and/or failure
  - Maintenance deficiencies:
    - inadequate or poor repair of damaged areas
    - inadequate or irregular maintenance

Appendix B3. A list potential physical factors contributing to the failure of concrete-lined spillways (adapted from Table 2 in Schweiger and others, 2019)

The list should be viewed as stimuli rather than as an exhaustive checklist.

- Thinning of the conveyance channel slab above slab drains
- Large variations in slab thickness
- Limited slab reinforcement consisting of one-layer (or less) light reinforcement in the slab
- Lack of continuous tension reinforcement across slab joints
- Corrosion and failure of reinforcing bars across cracks
- Slab joints without keys
- Slab placement sizes too large to control cracking
- No waterstops in slab joints or missing joint sealant
- Hydraulic pressures and flows transmitted beneath slabs through open cracks and joints
- Increase in spillway discharge shortly before slab failure
- Plugging of drains or collector pipes by tree roots
- Plugging of drains or collector pipes by soil due to incompatible or unfiltered gravel drains
- Plugging of drains or collector pipes wrapped in geotextile by clogging of geotextile
- Plugging of drains or collector pipe by vandalism (dropping stones or trash into manholes)
- Plugging of drains or collector pipes by iron bacteria, precipitate, or calcium deposits

- Plugging or collapse of drains or collector pipes from structural deterioration of the pipes
- Plugging of drainpipes from unintended modification (grouting)
- Flow into the slab underdrain system from cracks, open joints or slab defects that exceeds the capacity of the drain system
- Flow into the slab underdrain system from surface runoff on the landside of the spillway training walls that exceeds the capacity of the drain system
- Flow into the slab underdrain system from foundation seepage that exceeds the capacity of the drain system
- Lack of redundancy in collector drains and drain outlets
- Unfiltered drains; the gravel envelope may not serve as a filter and allows soil to pass through the drain system creating voids under the slabs
- Under slab drains crossing joints in the slab
- Weathered rock and completely weathered rock that is soil-like materials as slab foundation, without appropriate modification of the chute design, resulting in potentially erodible material beneath the slab and lack of foundation bond with concrete
- Less rigorous foundation preparation resulting in lack of foundation bond with concrete
- Extended drought impacts on foundation materials
- Insufficient anchorage, due to limited anchor development in the concrete, short anchor length, inadequate grouting or grout strength, and/or installation in weak foundation material
- Relatively high spillway flow velocities in the downstream conveyance channel for higher spillway discharges
- Lack of durability and effectiveness or slab repairs
- Spalling and/or delamination of concrete at slab joints
- Projecting transverse slab joints from construction or movement
- Hydraulic jacking from missing drain outlet covers or poorly placed drain outlets
- Headcutting erosion from downstream channel
- Groundwater pressures
- Spillway training walls not high enough to contain flows
- Spillway control structure has potential to become obstructed with debris
- Spillway gates, gate openings, or other opening at control structure have potential to be mis-operated during flood resulting in unbalanced spillway flows and overtopping of spillway wall(s)
- Spillway gate openings or other openings at control structure have potential to become clogged during flood event resulting in unbalanced spillway flows and overtopping of spillway walls
- Rocks or other debris in spillway and stilling basin causing ball milling of the concrete
- Profile of ogee control section under designed creating excessive negative pressures on crest that can destabilize the structure
- Cavitation

Appendix C – Supplementing Chapter 4

Appendix C1. Lessons on frequency of visits

The following points are worth considering when deciding upon the frequency of visiting a spillway:

- The past is not always a good indication of the future
    - “Past operational history may or may not be any indication of future performance” (p321, Trojanowski, 2006)
    - “As demonstrated by the Oroville Spillway incident and many other dam incidents, an extended period of apparently successful operation cannot be assumed to be predictive of equally successful future operation” (p2035, Schweiger and others, 2019)

- Timing is everything
    - “The Oroville Dam spillway incident was caused by a long-term systemic failure” (pS-1, California Department of Water Resources, 2018)
    - “Most spillway and outlet works structural defects and deterioration develop progressively” […] “Some problems arise suddenly. Full-capacity use during storms, flooding, or high-velocity releases can cause serious damage. For that reason, special inspections should be conducted after such events, or after seismic activity or other circumstances that may have affected the spillway and outlet works structures” (p1, Veesaert, 2004)
    - “The first event in the sequence of events leading to a stagnation pressure spillway failure [...] can go undetected by an inspection or can develop rapidly during extreme spillway flows” (p2036, Schweiger and others, 2019)
    - “It is unlikely to both gain optimum access and observe unusual stresses from operation during a single inspection of a structure. These two goals are often incompatible, and inspection objectives may have to alternate from one inspection to the next. Visits under different conditions can provide a comprehensive view of a structure's safety. For example, a dry conduit may display no visible joint problems, but just after dewatering, water might be seen spurting from some leaky joints into the conduit” (p16, Veesaert, 2004)
    - “It is anticipated that the supervising engineer will need to visit the reservoir at least once a year to be effective in his or her role” (p60, ICE, 2014)
    - “High risk reservoirs in Scotland are typically visited at least twice by a Supervising Engineer”
    - “Intermediate inspections frequency is normally specified in various country dam safety codes and guidelines, but preferably performed on an annual basis, or at least biannually, especially where there is a high probability that dam failure could result in loss of life” (p125, Adamo and others, 2020)

- A greater frequency of close supervision is recommended after a reservoir has undergone intrusive spillway repairs or where a defect has been previously been noted
- The benefits of physical examination are globally acknowledged
- "Visual observation can readily detect indications of poor performance such as offsets, misalignment, bulges, depressions, seepage, leakage, and cracking. More importantly, visual observation can detect variations or spatial patterns of these features" (p112, Adamo and others, 2020)
- "Close-up field inspection [is required] to observe, probe, sound and photograph all spillway features." […] "When conducting a spillway assessment, there is no substitute for physically examining all features of the spillway" (p2029, Schweiger and others, 2019)
- "The general technique for visually inspecting spillways and outlets is to examine each feature up close" (p99, Central Water Commission, 2018)

Appendix C2. Capturing visual data in different operating conditions

There are certain good and bad practices that can make the data either invaluable or worthless. Table C1 contains a selection of good and bad practices when taking videos or photographs. It can also be useful to consider the following when deciding on what technology to use:

- What resolution is required?
- Is there the opportunity for multiple benefits, for example to detect longterm trends?
- If CCTV is being contemplated, is the lens self-cleaning?
- How large are the digital files?
- How will data be stored and backed-up?

Table C2: A selection of good and bad practices when recording video or photographs

Bad practices recording visual data	Good practices recording visual data
Shaky/bouncy videos are difficult to view.	Use a gimbal device or tripod to keep footage steady. Some action cameras have picture stabilisation in-built.
Long video footage can be very tedious to watch and will not keep the attention of viewers.	Take short video clips/ footage. Avoid being more than 1-2 minutes. There are software solutions that place images in context. An example is https://tssvirtualtours.s3.eu-west-2.amazonaws.com/Hoddlesden/Hoddlesden.html
Footage/photographs without reference points makes it difficult for a third party to understand location or position.	Take a wide shot to provide context and scale. This helps represent the human's peripheral vision. A commentary on the video can describe the position of the footage along the spillway, for example, looking upstream or downstream.
Moving too quickly, irregular zooming in/out and panning around too much can make a film difficult to watch.	Videos need to be structured. Arrange training or speak to a specialist for advice and understand the rules for filming. Experienced drone operators are a good source for insights.
File names are not easy to understand.	Produce a file naming convention that is self-explanatory and consistent.
Can be difficult to re-navigate to a specific reference point in the footage.	Consider adding digital tags in video.

Appendix D – Supplementing Chapter 5

Appendix D1. The Work at Height Regulations 2005

The Work at Height Regulations, formally incorporated within the Construction (Health, Safety & Welfare) Regulations (since withdrawn and now incorporated within the Management of Health & Safety at Work Regulations) and the Workplace (Health, Safety & Welfare) Regulations address all issues surrounding working at height, in all industries.

The Regulations were introduced into UK Health and Safety law in 2005 following the inclusion of the 2001, EU 'Temporary Work at Height Directive' into European Health and Safety law. The Regulations set out the hierarchy of measures you should follow when carrying out work at height.

Following the risk assessment, this hierarchy should allow you to select the most appropriate methods and equipment for work at height. The overriding principle is to prevent, so far as is reasonably practicable, any person falling a distance likely to cause personal injury:

1. **Avoid** the risk by not working at height – where it is reasonably practicable to carry out the work safely other than at height then you should do so.
2. **Prevent** falls – where it is not reasonably practicable to avoid work at height, you should assess the risks and take measures to allow the work to be done while preventing, so far as is reasonably practicable, people or objects falling. This might include ensuring the work is carried out safely from an existing place of work or choosing the correct work equipment to prevent falls.
3. **Minimise** the consequences of a fall – where the risk of people falling remains, steps should be taken to minimise the distance and consequences of such falls. This includes the correct selection and use of work equipment.
4. At all stages give **Collective** protective measures, for example, guardrails, precedence over personal protective measures, for example, safety harnesses.

The work at height hierarchy is illustrated in **Figure D1**. Within this framework, the Regulations require you to:

- compare it against the benefits of an examination from touching distance
- questions where the resulting data will be stored and how it can be accessed by the reservoir manager/undertaker
- assess the risk to help you decide how to work safely
- follow the hierarchy for safe work at height – Avoid, Prevent, Minimise, and always give Collective measures priority
- plan and organise the work taking account of weather conditions and the possibility of a rescue, for example, worker suspended from a lanyard following a fall
- ensure those working at height are competent to do so
- make use of appropriate work equipment

- manage the risks from working on or near fragile surfaces
- inspect and maintain the work equipment to be used and inspect the place where the work will be carried out, including access and emergency egress

Most Desirable → Least Desirable

Most Desirable ↓ Least Desirable

1. Avoid work at height		
2. Carry out work from an existing place of work		
-	Collective	Personal
3A. Work equipment which prevents a fall	Guardrails, scaffolding, mobile towers, multi-user mobile elevating work platforms (MEWPs)	Personal fall prevention and work restraint systems, Single user MEWPs
3B. Work equipment which minimises the distance and consequences of a fall	Safety nets ≤2m below Soft landing ≤2m below Safety nets ≥2m below	Personal fall protection systems used in: Fall factor 0 Fall factor 1 Fall factor 2
3C. Work equipment which minimises the consequences of a fall	Soft landing systems, safety nets at low level ≤6m below	Injury reduction systems, for example, life jackets
3D. Work equipment which does none of the above	Ladders and unguarded platforms	

Figure D1: Work at height hierarchy

Appendix D2. Asset considerations when developing an access strategy

- **The intended frequency of use** – Consider that although temporary access methodologies may sit lower in the work at height hierarchy, any solution must be reasonably practicable. So, while a permanent installation may be preferred from a work at height hierarchy perspective, the costs associated with that system if intended for use only infrequently may be prohibitive and a temporary solution may prove more appropriate.
- **Any potential effect on the performance of the asset** – Consider the effect of a permanent installation on the flow of water, interference with access to any associated infrastructure- roadways pipework, electrical installations.
- **Installation risks** – While temporary scaffold platforms, for example, may represent a preferred work at height solution for an end user, consideration must be given to the risks associated with the installation. If repeated installation and removal of that platform is technically or logistically challenging and carries significant risk to the installer, then it may not be the best final solution.
- **Inspection and maintenance requirements of the system** – Consider corrosion potential, statutory inspections[34] for fixed access assets, the cost and frequency of these inspections and potential maintenance costs.
- **Training in the use of the system** – Some systems do not require specific training (for example, permanent steps) and safety notices displayed at the site will provide sufficient instruction to the user. Other systems of access require extremely high levels of competency and should only be undertaken by professional service providers. Regardless of the system, consideration needs to be given to the people using it, their physical abilities and limitations, their psychological willingness to use the system and their training requirements.
- **Protection of the public, security and vandalism risks –** Does the new system pose a security risk or vandalism target? Does it freely give access to trespassers to enter dangerous parts of the infrastructure and how will it be secured?
- **Accessories for the use of the system** – Accessories (for example, harnesses, ropes, fall arrest devices) require careful storage, regular inspection and re-certification by a suitably qualified person. Are there facilities available to do this or would these be best provided and used by a specialist work at height contractor?
- **Any other hazards introduced to the site by installation of the system** – for example, a system that facilitates work at height may introduce the hazard of dropped or falling objects onto the area beneath which was previously not present. Alternatively, if the system become inhabited by certain wildlife, the site could become off-limits during nesting period.

[34] Refer to the Provision and Use of Work Equipment Regulations 1998 (PUWER).

- **Cost of install and annual cost of maintenance** – The chosen system will carry a cost. Consider design, installation, operations and decommissioning costs for each system. Ultimately the chosen system needs to be considered reasonably practicable to implement.

Appendix D3. Rope access to Ryburn Reservoir dam and spillway

Access specialists studied the local aspects and developed an access strategy. Due to the height of the dam and the narrow walkway along the top, access options such as scaffolding and mobile elevating work platforms were deemed not possible.

Following a reconnaissance site visit, a safe system of work was formulated. The chosen system enabled operatives to abseil from the top of the dam to inspect the whole structure within touching distance.

The safe system of work also covered rescue, where operatives could either be lowered to ground level or winched back to a position of safety at the top of the dam.

Temporary anchors were established on the walkway for the duration of the works. The minimal site set up and ease to demobilize each day allowed the team to be reactive to the weather and remove all equipment each day, thus eliminating the potential for any unauthorized access or vandalism.

A comprehensive factual report was produced including photographs and drawings. These confirmed areas of concrete defects (cracking, spalling, staining etc.) and enabled suitable repairs.

Two specialists abseiling the concrete dam

Narrow walkway affecting access strategy

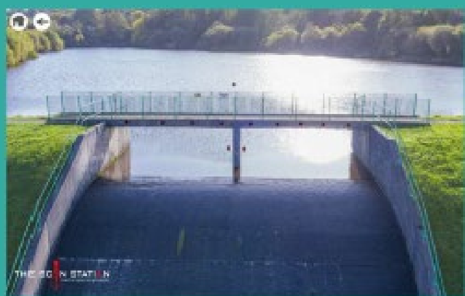
This case study was kindly produced by Simon Enderby at Up and Under

Appendix D4. UAV survey at Hodlesden Reservoir

A visual inspection of the spillway was performed using a UAV equipped with a high-resolution camera. To achieving a safe, high-quality survey there were four important factors:

1. A highly experienced pilot with over 500 flight hours
2. Planning – The asset and its surroundings were carefully studied and a detailed flight plan was designed to maintain line of sight. The weather forecast informed the chosen survey date
3. On-site evaluation – The pilot carried out a dynamic risk assessment on the day according to the weather conditions. The data collection routine was adapted to suit local conditions
4. Data collection – Data capture and chosen equipment was designed to yield:
   - A high resolution Orthomosaic of the asset and its surroundings
   - Cascading detailed asset photography, providing context as well as detail

The data was processed to produce detailed mapping and photography of all asset elevations. An online viewing platform clearly presents the outputs in an easy to navigate structure: https://tssvirtualtours.s3.eu-west-2.amazonaws.com/Hoddlesden/Hoddlesden.html



UAV output

This case study was kindly produced by Albert Fit at The Scan Station

THE SCAN STATION
SURVEY & INSPECTION SPECIALISTS

Appendix D5. Suggestions for commissioning UAV survey

A licence to operate does not indicate that a UAV operator is competent to obtain good quality data and process it. Here are some suggestions for improving the probability that the UAV operator will provide useful and good quality outputs:

1. Before commission, request to see:
    a) qualifications, licences and insurances
    b) examples of post-processed outputs. Images/video should be suitably composed, exposed, focused and free of excessive noise

2. Set a clear specification, explaining the scope and purpose for the survey. Consider:
    a) setting the required detail, minimum size of defect and coverage. An experienced UAV operator will be able to calculate the most appropriate resolution and proximity (ground sample distance[35])
    b) specifying the required data format, accessibility and duration. A web-based platform can offer easy access but might not be suitable for long-term storage
    c) specifying a folder structure and file naming convention that is self-explanatory. It can be useful to catalogue the detailed photographs and reference them to a broader model, such as an orthomosaic map, a 3D inspection model, a 3D point cloud or unwrapped orthomosaic maps for individual elevations
    d) asking for clarity on how accuracy of outputs will be obtained, such as number of ground control or other reference points

3. Before the survey, request a risk assessment and flight plan. This should explain how features will be surveyed and what measures are in place to mitigate hazards. Aspects that should be addressed include:
    a) battery life and avoiding pollution in a crash
    b) collision damage protection (sense and avoid)
    c) wind speed in which the UAV can operate and ability to counter sudden changes in wind
    d) tailoring the size of aircraft to the spaces that require surveying

Before the survey, ensure that the UAV operator obtains the necessary approvals to fly at the site.

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[35] Ground sample distance represents the size of one pixel on the ground. If all 1mm cracks need to be detected, the ground sample distance must be at least 0.25 mm.

Appendix E – Supplementing Chapter 6

Appendix E1. A list of useful equipment for visual examination (adapted from Table 4 in Firoozfar and others, 2018)

The list should be viewed as stimuli rather than as an exhaustive checklist.

- **Site specific inspection checklist** Helping with consistency and completeness of inspection effort
- **Sketches of spillway components** To document and reference abnormalities for easy tracking
- **As-built drawing set** Reference for documentation
- **Heavy-duty brush** Small debris and vegetation removal
- **Tape measure** Determine size, geometry and location of observed features
- **Laser measure** Quick measuring from wall to observed features
- **Survey wheel/tape** Determine location of observed features
- **Crack gauge** Determine size of cracks
- **Torch** Light source for dark areas
- **Camera** Take photos and videos of the observed features
- **GoPro/push cameras** Monitoring underdrain system
- **Hammer** Debris removal, manual hammer impact testing for qualitative identification of material strength and voids under concrete lining
- **Metal rods** Probing joint gaps
- **Heavy chain** Chain drag testing for identifying voids under concrete lining
- **Plumb bob/level** Check deflections of walls or slabs
- **Watering can and dye** Check extent of permeability of cracks and where the water emerges

Appendix F – Supplementing Chapter 7

Appendix F1. Typical stages of a non-destructive survey

1. Documentation review – an assessment of any records of the site will improve an understanding of the site and planning of the survey. Visual survey records, including photographs can also help.
2. Site visit – walking through or near the site improves understanding of the nature of the site, ground/ slab conditions and access considerations. This can improve the quality of a proposal.
3. Site works – using a range of methods deployed across a grid or along survey lines, as appropriate. Data capture is usually achieved through one or more receivers attached to the surface. Spatial location information associated with the survey data is also captured at the same time.
4. Data processing, analysis and interpretation – some processing is straightforward, while some is very time-consuming. For example, radar data processing takes a while as it involves large datasets, complex software algorithms and competent experienced geophysicists to process and interpret the data. Time spent on data collection and processing are typically the major cost elements. Therefore, the larger the survey area, the more time is required for the survey. This is generally linearly proportional; for every day spent collecting data on site, an additional 2 to 5 days are required to process, interpret and report the data. The amount of processing time will depend on the method used.
5. Reporting – the outputs agreed with the client typically form a factual or interpretative report. This normally includes graphs and/or drawings with interpreted results. The report and drawings normally state the accuracy of the data, any calibration undertaken, limitations, the area covered by the investigation and recommendations for intrusive works.

Satellite-based surveys follow similar stages except for not requiring site works and processing may take longer.

Appendix F2. Typical stages of a non-destructive survey

- Agreeing the specification – a suite of intrusive investigation works can be agreed and specified following a review of the available construction documents, visual condition survey records and geophysical survey report findings.
- Site investigation – these constitute on-site tests (such as half-cell potential), intrusive investigations (breaking out construction details) and concrete sampling for subsequent determination of material properties in the laboratory.

- Laboratory work – submission of material samples to a suitable laboratory[36] for testing. Compressive strength, chemical composition and petrographic examination for determination of material constituents and evidence of deterioration.
- Reporting – the reports should serve to provide the client with the context of and summary of the work leading up to the intrusive investigations, as well as how findings affect the initial hypothesis on construction arrangement and condition. This will inform the design of remedial works.

Appendix F3. Case study: Using GPR to detect voids and confirm construction features

The Canal and River Trust commissioned an investigation on spillway construction details and the existence of voids. A 1,500MHz GPR system (**Figure F1**) was chosen as it provides high resolution data to depths of 500mm and gives a permanent record. It is also capable of imaging multiple layers of construction detail (location of internal metalwork/ reinforcement) and voids.

Figure F1: A 1.5GHz GPR deployed on a concrete spillway

Figure F2 show 2 GPR 'B-scans' taken in orthogonal directions on the spillway. The top B-scan indicates large reinforcing bars in one direction and the bottom Bscan indicates a tighter spaced reinforcing mesh. The depth of concrete cover was measured between the spillway surface and the top of the hyperbolic reflectors.

[36] UKAS-accreditation for laboratory tests is advised in the UK.

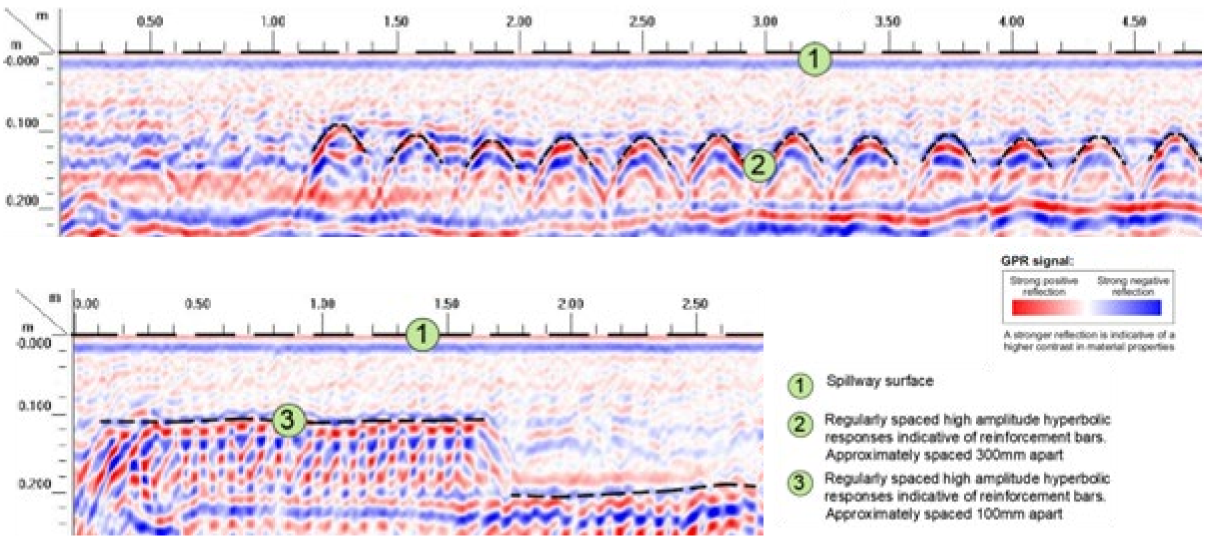

Figure F2: Two GPR 'Bscan' outputs revealing location and characteristics of reinforcement

The GPR results were also presented in 'plan' view as a colour contour map (left image in Figure F3) and the interpreted rebar cover depth values (right image in Figure F3). This enabled the engineer to identify any anomalous areas of shallow cover depth, variable cover depth or the absence of any reinforcement.

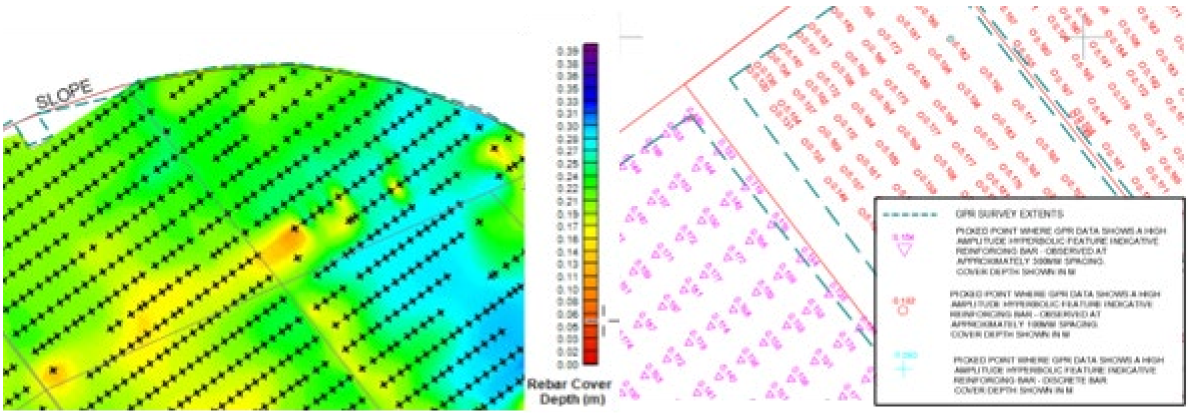

Figure F3: GPR results showing rebar cover depths in two different formats

The GPR outputs also helped identify the thickness of the concrete slab; manifested as a slighter higher amplitude horizontal reflector directly below any reinforcement, as highlighted by dotted line in figure F4.

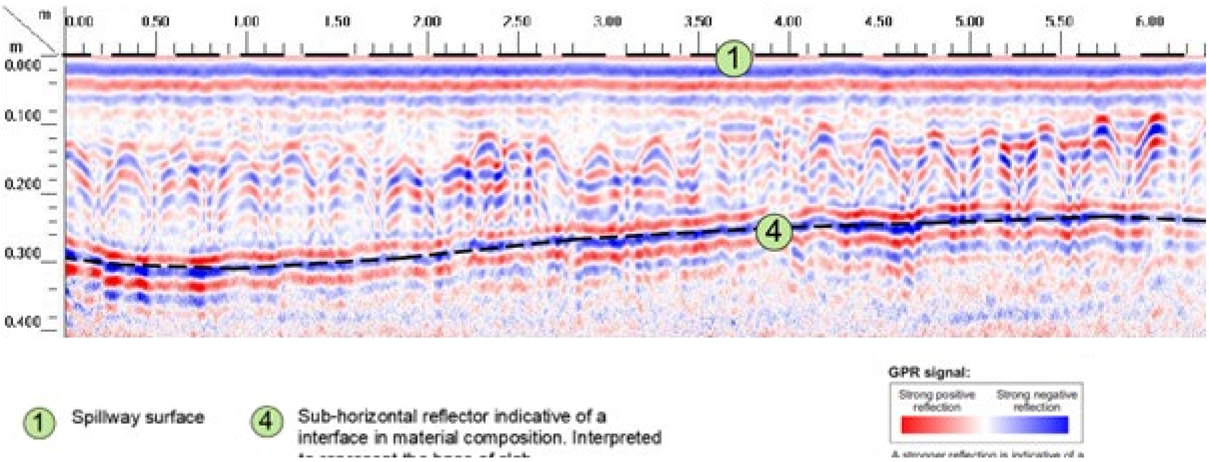

Figure F4: GPR output revealing thickness of concrete

Mid-frequency GPR (400MHz) was deployed across the spillway to detect voids or deeper features. The presence of a void constitutes a contrast in dielectric (electrical) properties and generates anomalous reflections. The nature and strength of these reflections are dictated by the void size, fill and orientation, and nature of the surrounding ground. **Figure F5** revealed numerous areas of disturbed, high amplitude reflectors, relating to either possible voiding, increased saturation or more granular deposits (or a combination thereof).

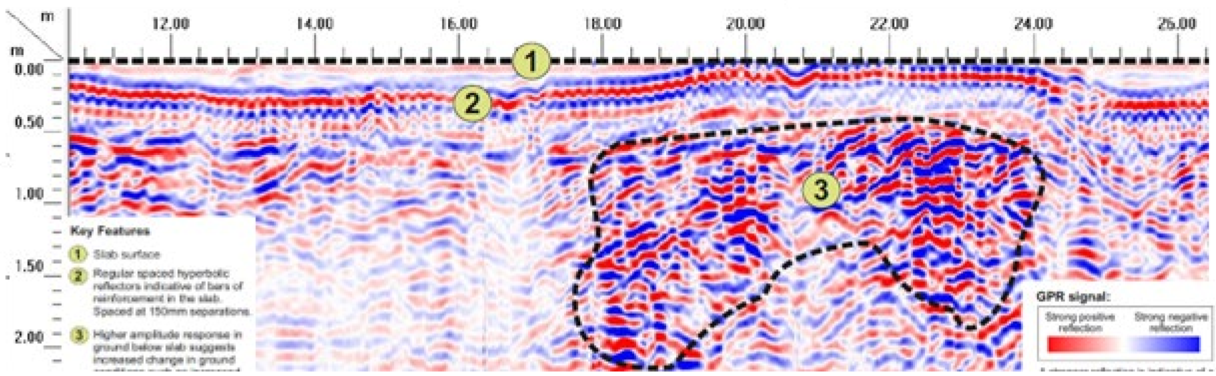

Figure F5: GPR output from a medium frequency 400MHz

The responses were transposed onto a drawing and presented as anomalous areas in ‘plan’ view, Figure F6. This helped inform where to undertake targeted intrusive investigations.

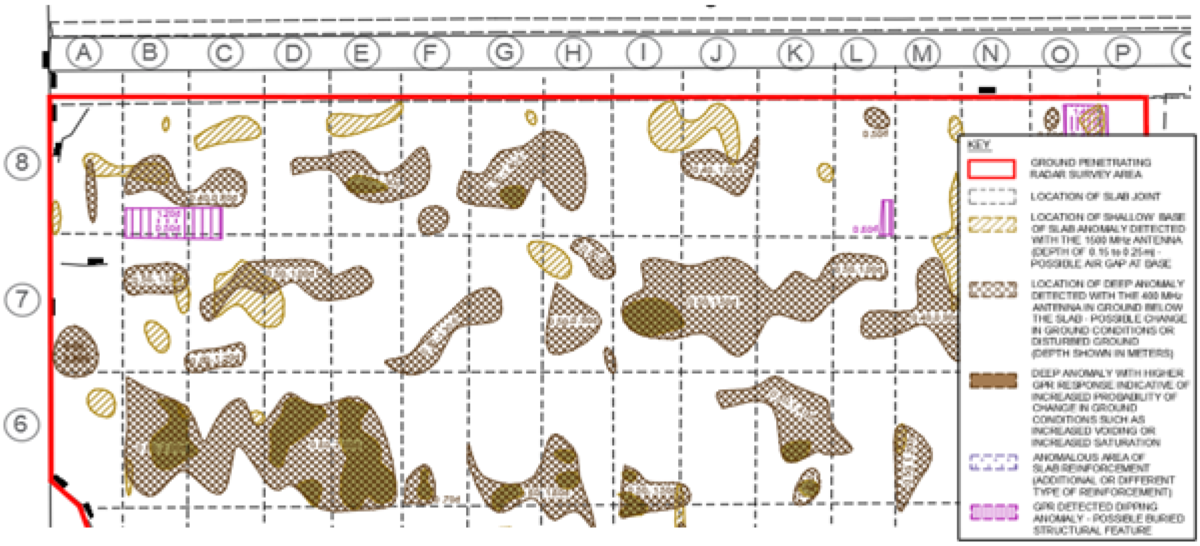

Figure F6: Illustration of voids under a spillway using GPR

Appendix F4. Case study: Investigating spillway seepage and slab construction

A 10m x 40m concrete spillway at a reservoir in Derbyshire (UK) was exhibiting seepage from number of joints (Figure F7). A GPR survey using multiple frequencies was carried out to determine the slab construction and presence of any voids that may indicate water pathways below the slab.

Figure F7: Visible wet spots at spillway joints

GPR data was collected in a grid of survey lines spaced 0.5m apart across the spillway using an antenna with 1.5GHz frequency. This revealed the presence of top and bottom rebar in the slab, the slab thickness and the presence of anomalous areas at the base of the slab.

A ‘heat map’ was created showing areas of greatest GPR response below the base of the slab Figure F8. A larger response indicates a greater change in di-electric properties of the ground, signifying the possible presence of voids (water-trapped or air-filled). At this site, the location of high GPR responses correlated to where seepage was visible on the surface. This information was then used to inform targeted, intrusive investigations, such as coring.

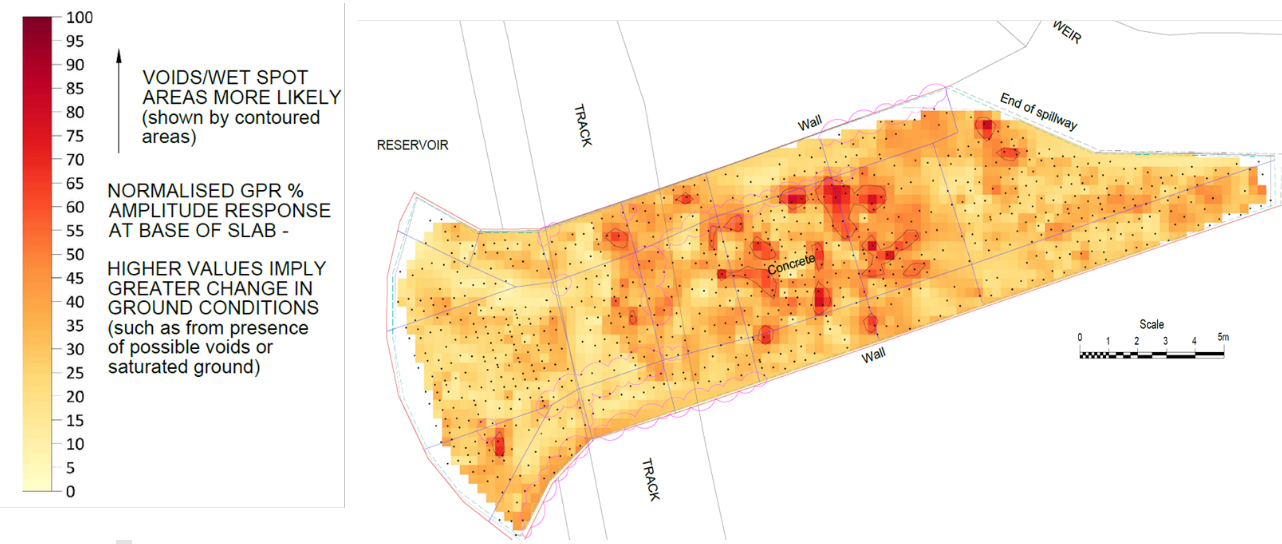

Figure F8: ‘Heat map’ indicating potential voids under the spillway slabs

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